Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

How FLUXNET data and models can improve knowledge on the water, evaporation at tower, grid, watershed, and continental scales

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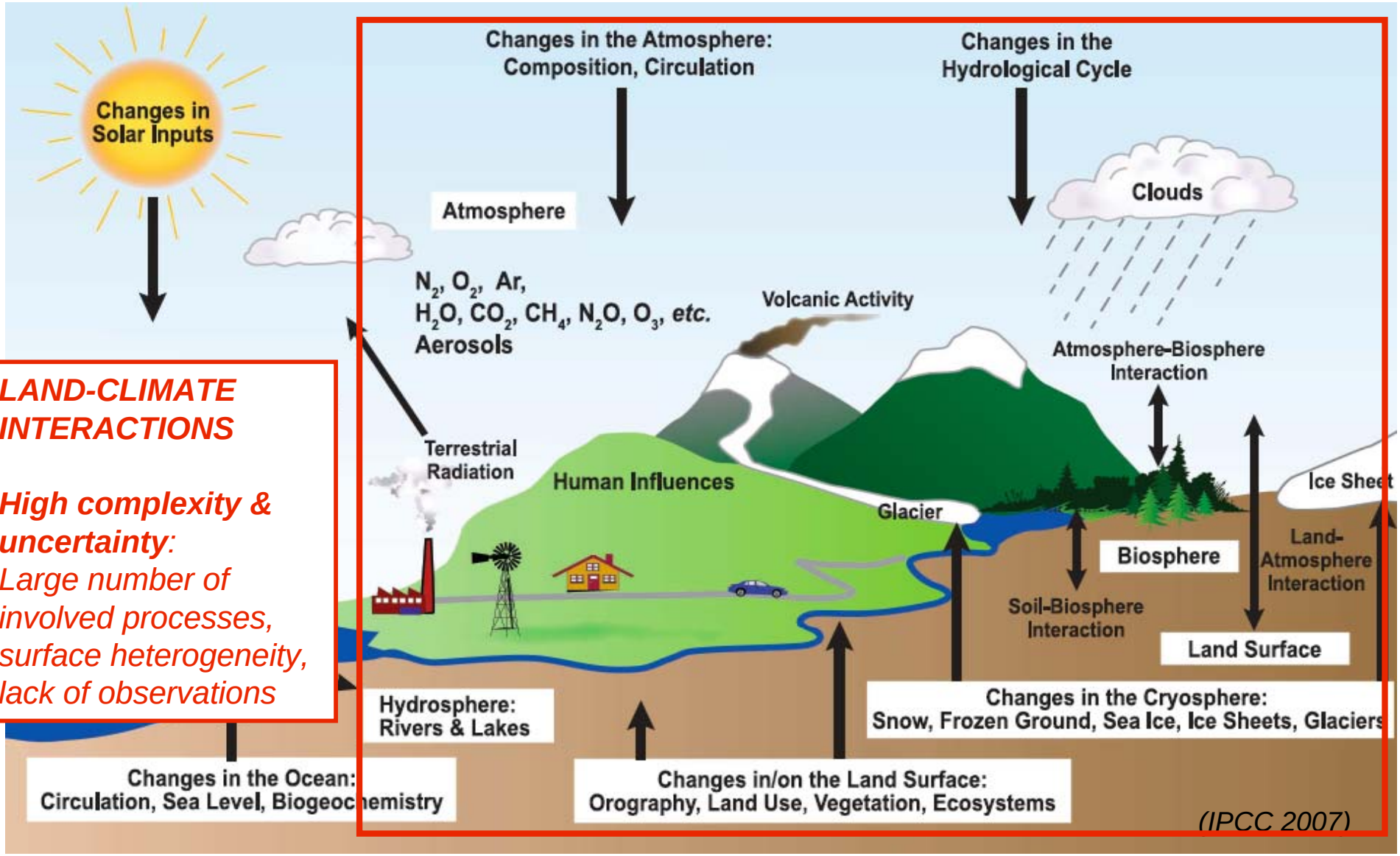
Outline

- Introduction
- Land-climate feedbacks and interactions:
  - Impact of soil moisture on temperature and precipitation
  - Impact on temperature variability, modifications with climate change
- Discussion: Using (FLUXNET and other) observations to diagnose coupling and validate models
- Conclusions

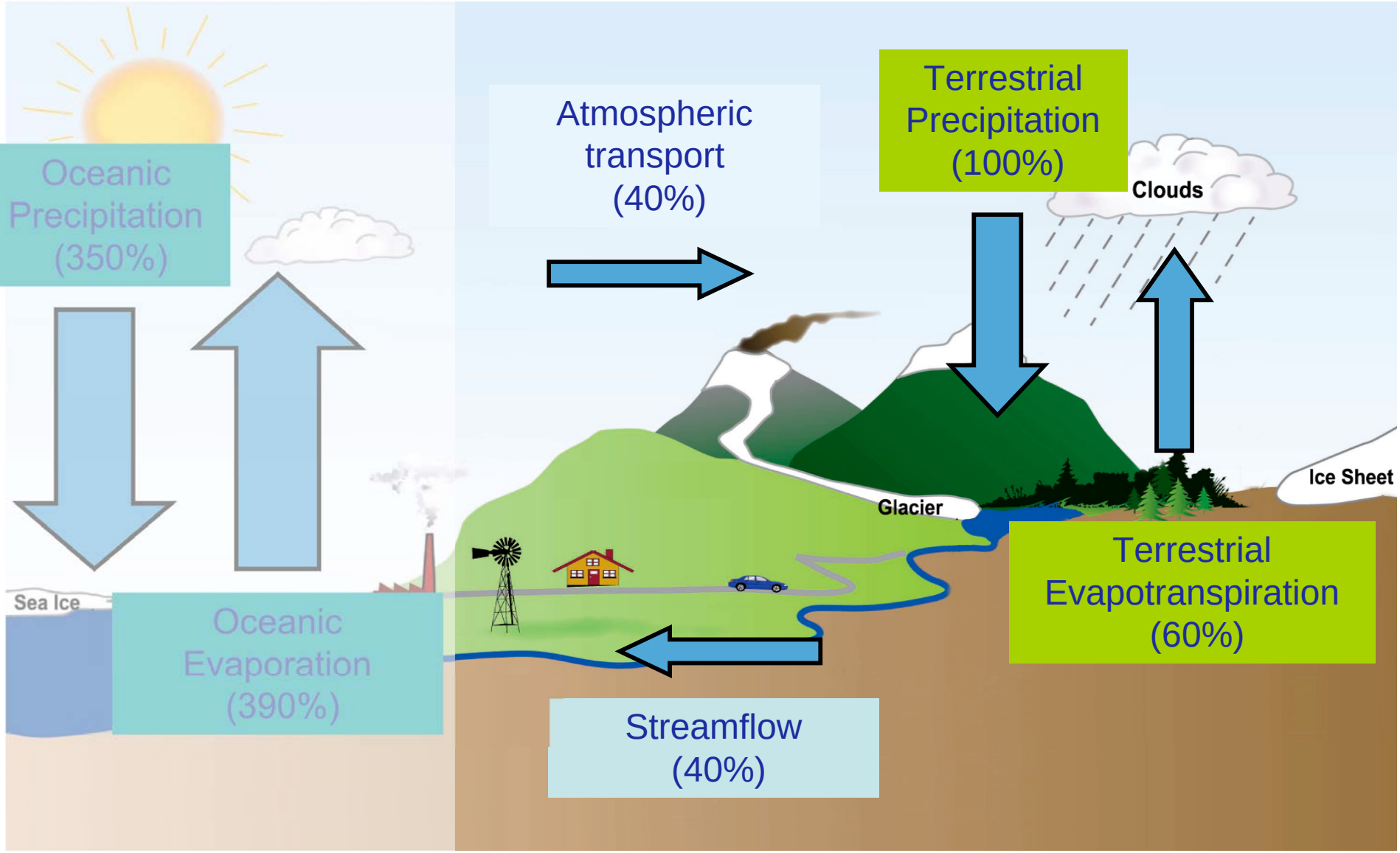
Introduction: The climate system



LAND-CLIMATE INTERACTIONS

***High complexity & uncertainty**:*
Large number of involved processes, surface heterogeneity, lack of observations

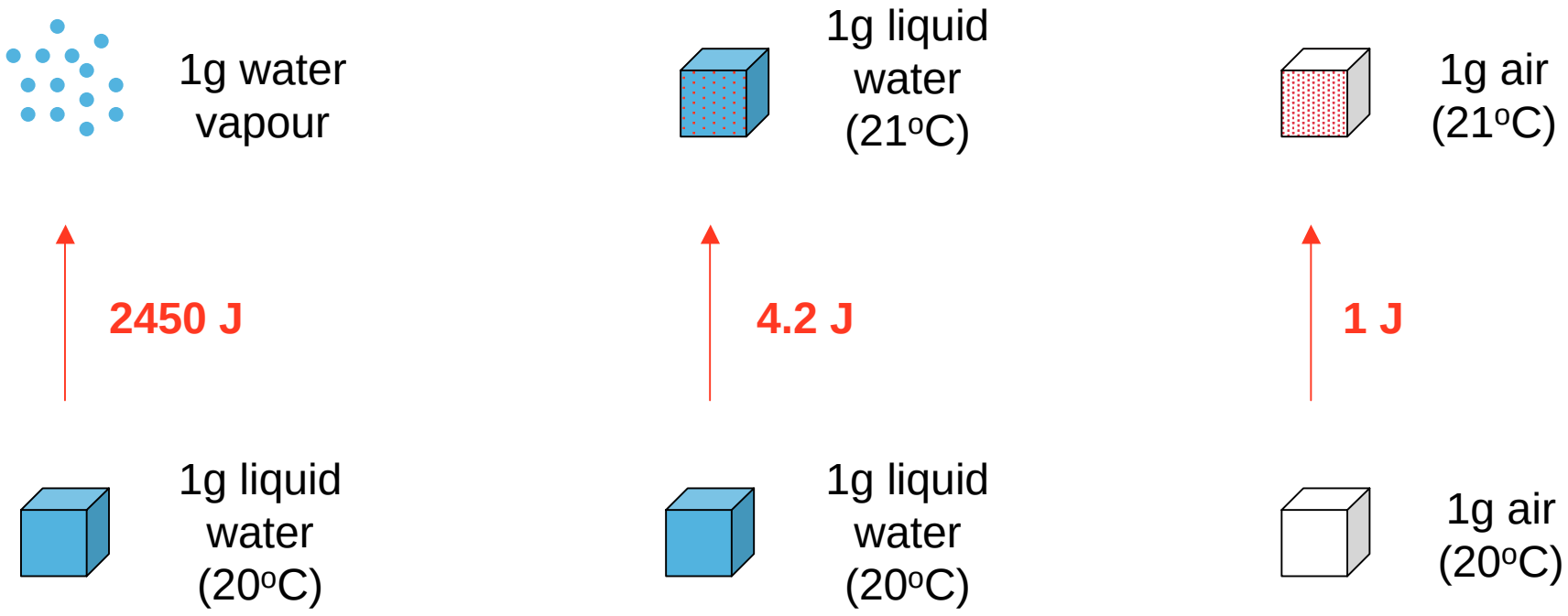
Soil moisture-precipitation feedbacks



(Flux estimates: Oki and Kanae, Science 2006)

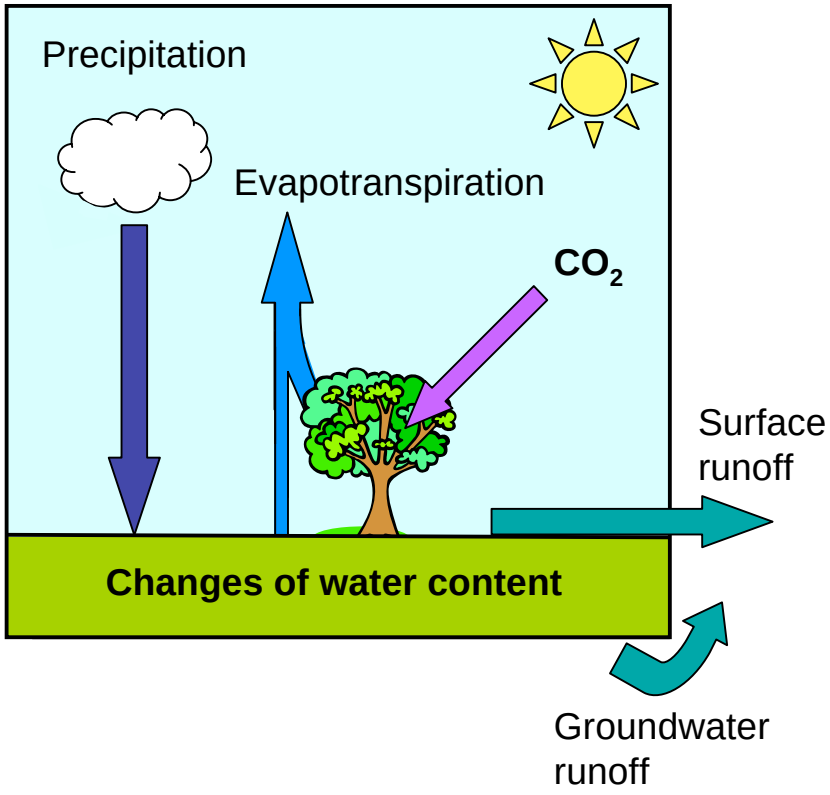
Evapotranspiration as energy flux

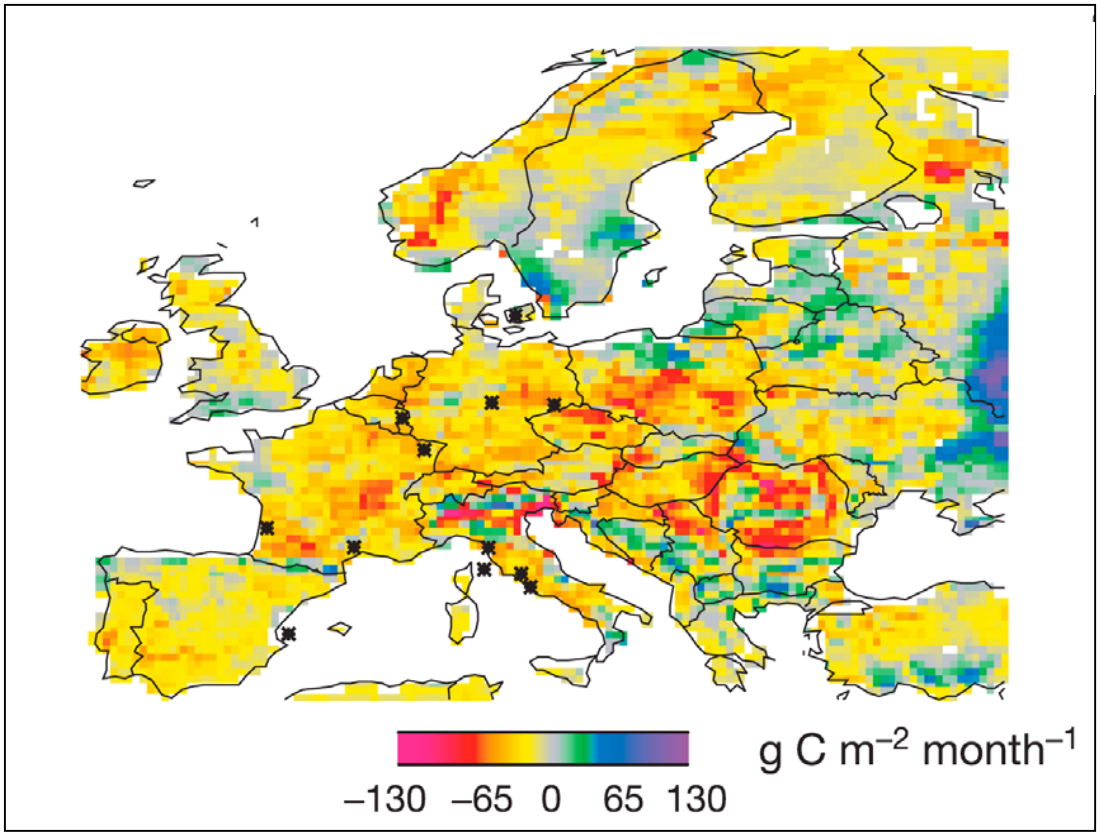
Evapotranspiration is a large flux of energy!



Vegetation - CO_2 interactions

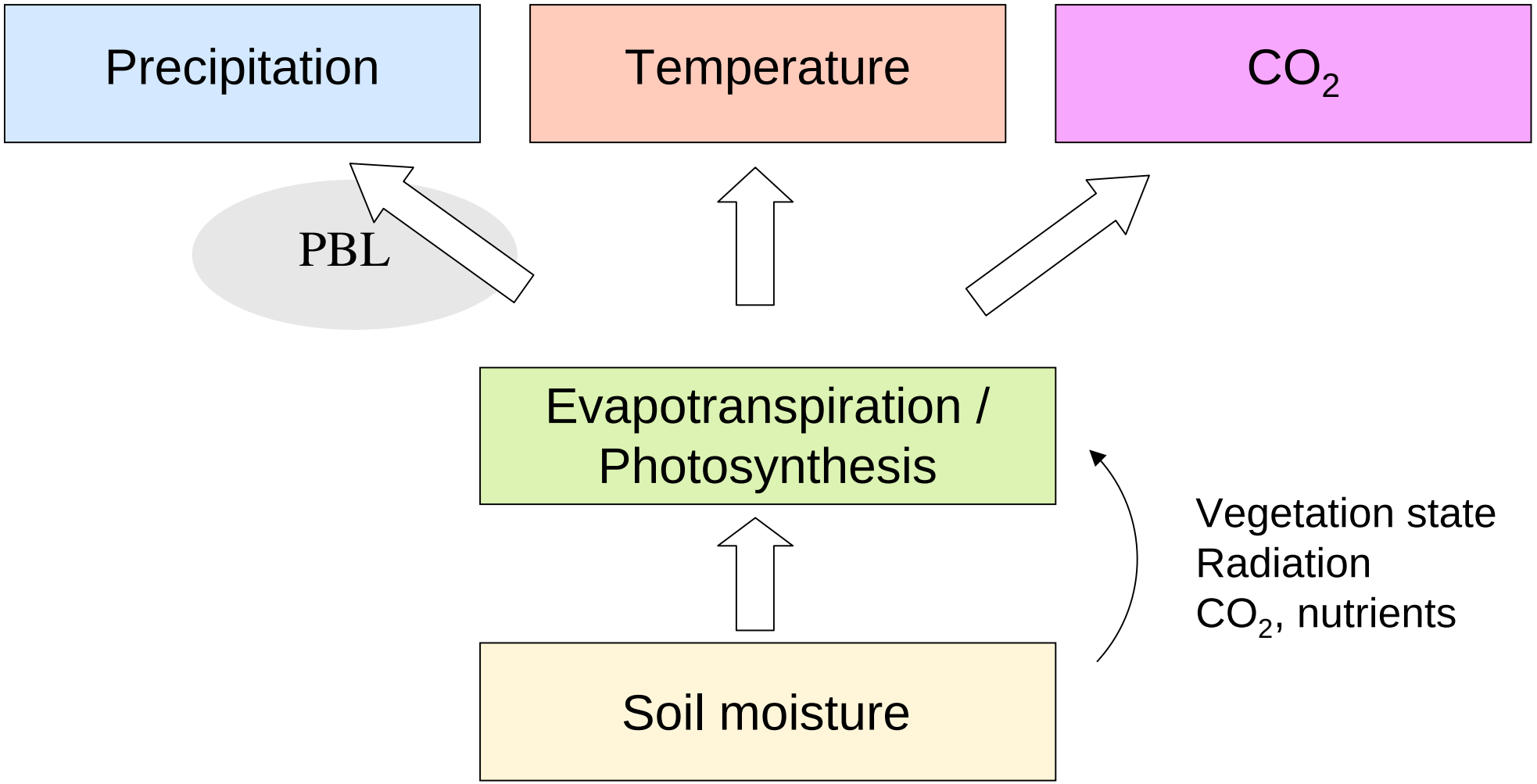
Europe transformed in carbon source in summer 2003 (heatwave/drought)





(Ciais et al., Nature, 2005)

Introduction



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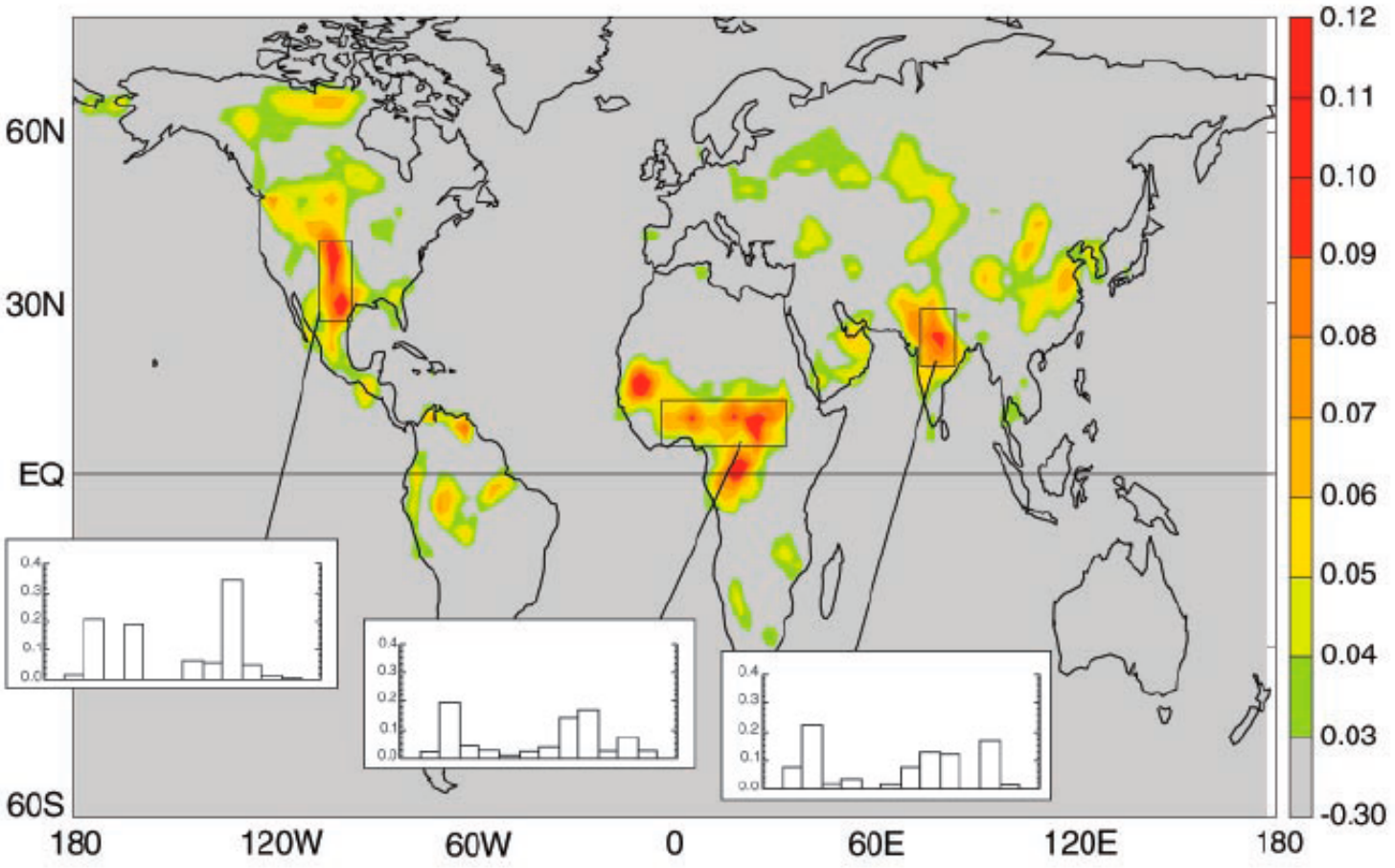
Modelling experiments: e.g. GLACE approach

Where is soil moisture controlling precipitation?

Global Land-Atmosphere Coupling Experiment (GLACE)
12 AGCMs, experiments for JJA 1994



$\Omega_P(S) - \Omega_P(W)$
[Precipitation]

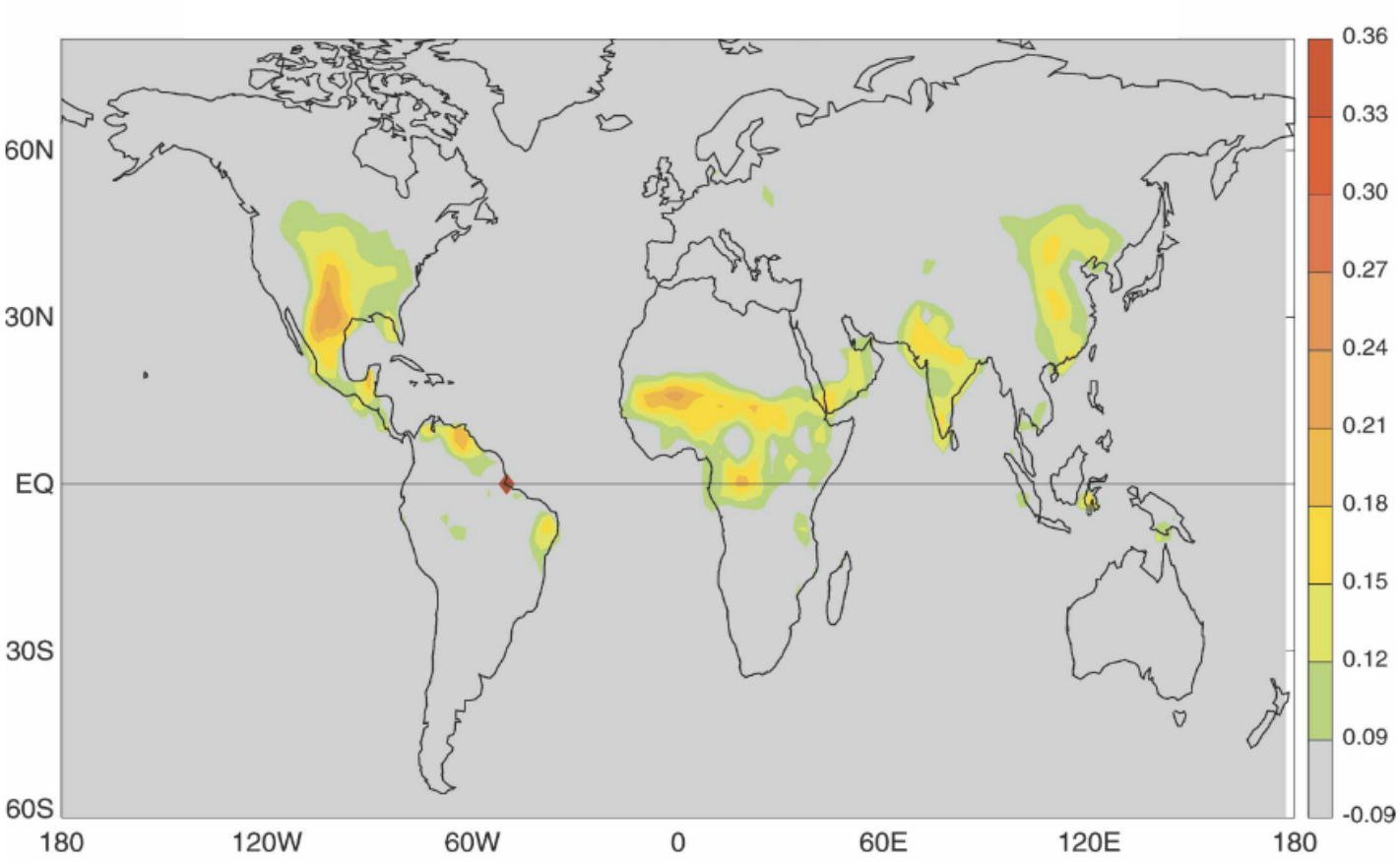
(Koster et al. 2004, Science)

Strong coupling in transitional zones between dry and wet climates

Modelling experiments: e.g. GLACE approach

Where is soil moisture controlling temperature?

Global Land-Atmosphere Coupling Experiment (GLACE)
12 AGCMs, experiments for JJA 1994



$\Omega_P(S) - \Omega_P(W)$
[Temperature]

(Koster et al. 2004, Science)

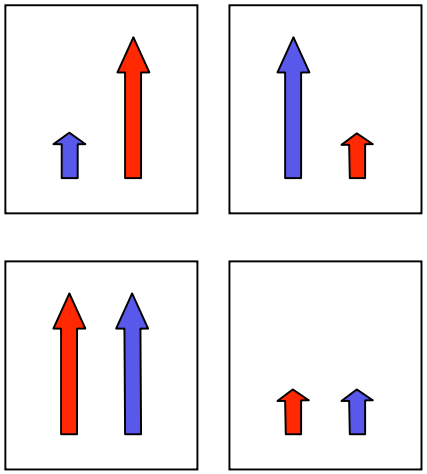
Strong coupling in transitional zones between dry and wet climates
NB: similar regions of strong soil moisture-precipitation and soil moisture-precipitation coupling

Comparison with IPCC AR4 GCMs

Indirect measure of coupling between soil moisture & T°:
Correlation between summer evapotranspiration and temperature $\rho_{(ET,T2M)}$

Negative correlation: strong soil moisture-temperature coupling (high temperature as result of low/no evapotranspiration)

Positive correlation: low soil moisture-temperature coupling (high temperature leads to high evapotranspiration)

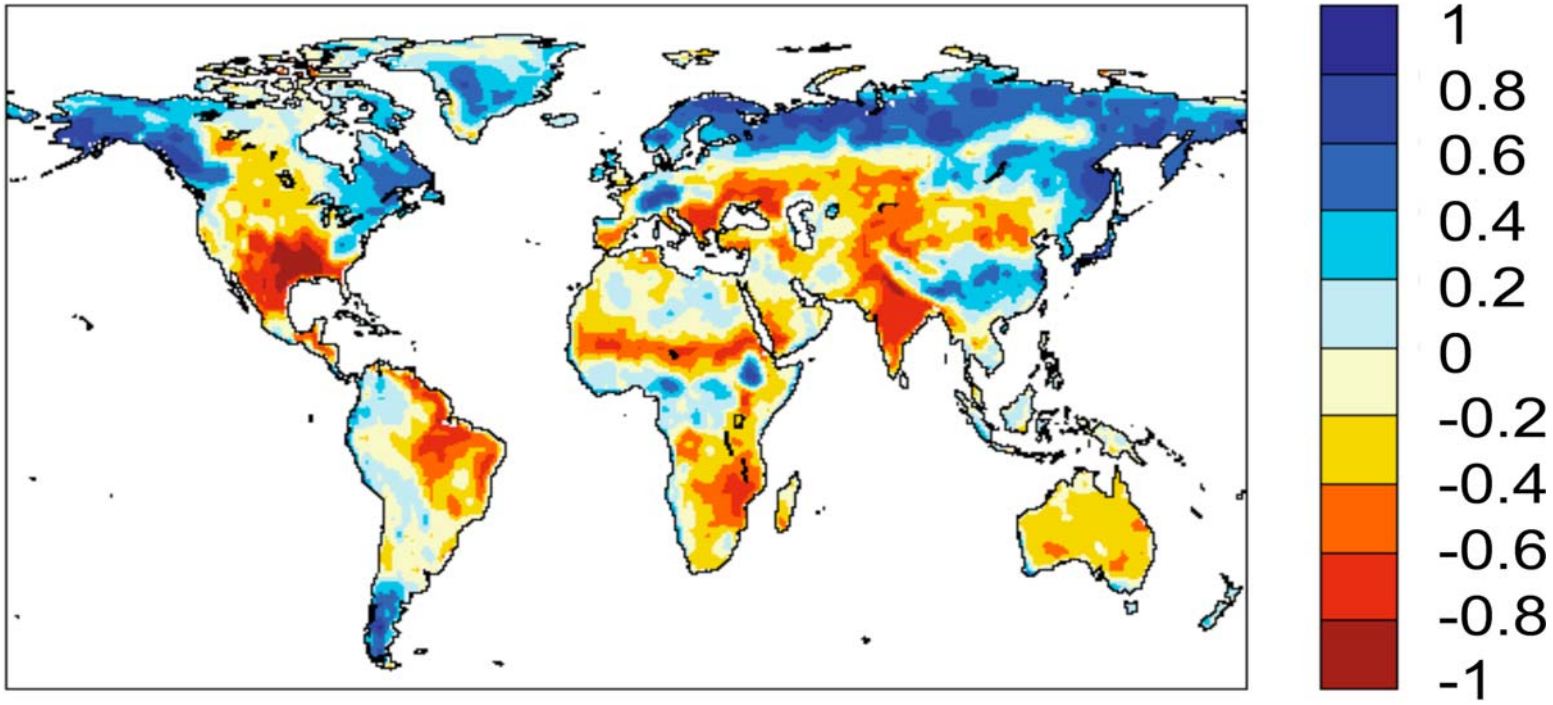


Model analysis: Correlation (T, ET)

Impact of soil moisture on interannual variability of temperature

(IPCC simulations: ECHAM5, GFDL, HadGEM1; JJA 1970-1989)

Correlation (temperature, evapotranspiration)

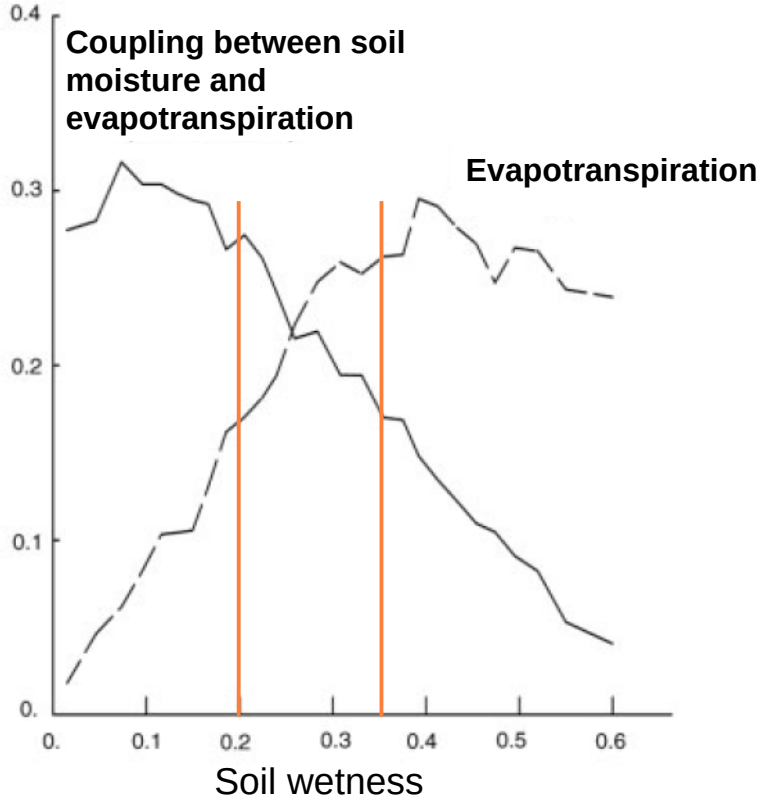


(Seneviratne et al. 2006, Nature)

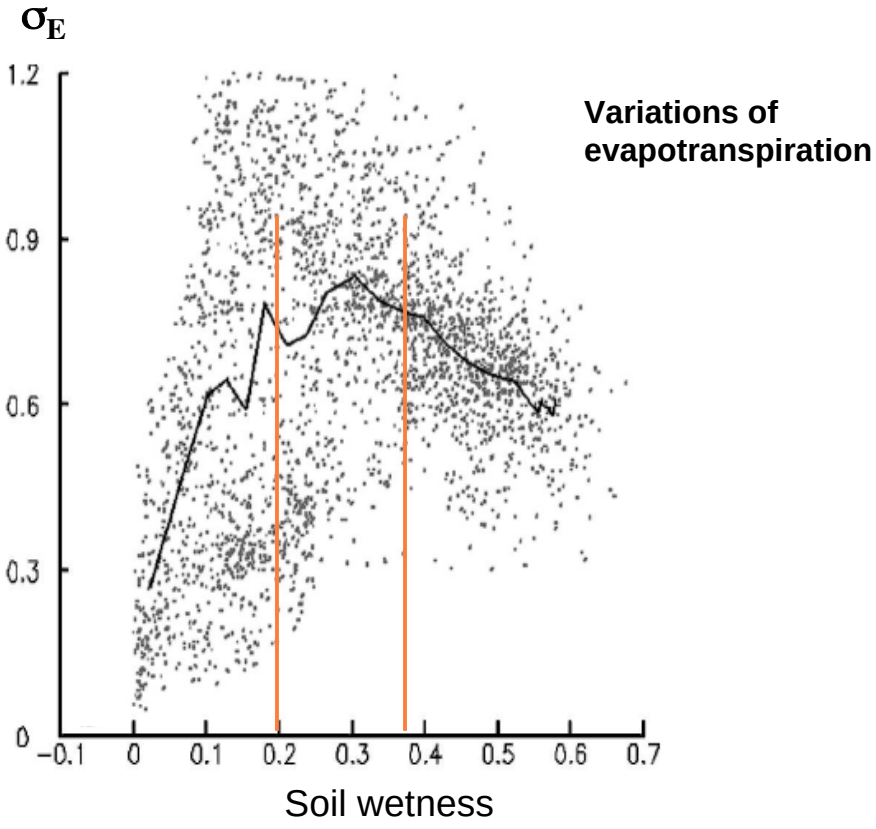
Similar regions of strong coupling; more general signal (e.g. includes Mediterranean region in Europe) → based on 20 years of data

Why strong coupling in transitional regions?

- **Wet climate:** Soil moisture has little impact on evapotranspiration/climate
- **Dry climate:** Evapotranspiration and variations thereof are small



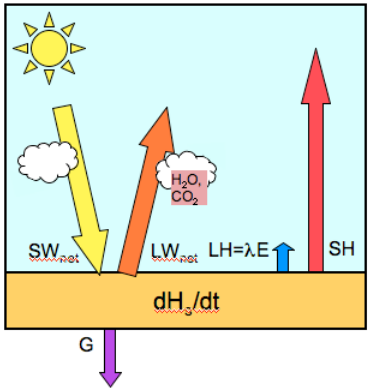
(Koster et al., 2004, Science)

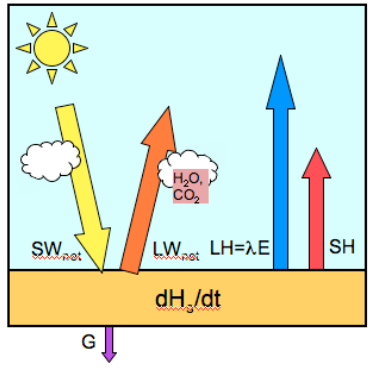


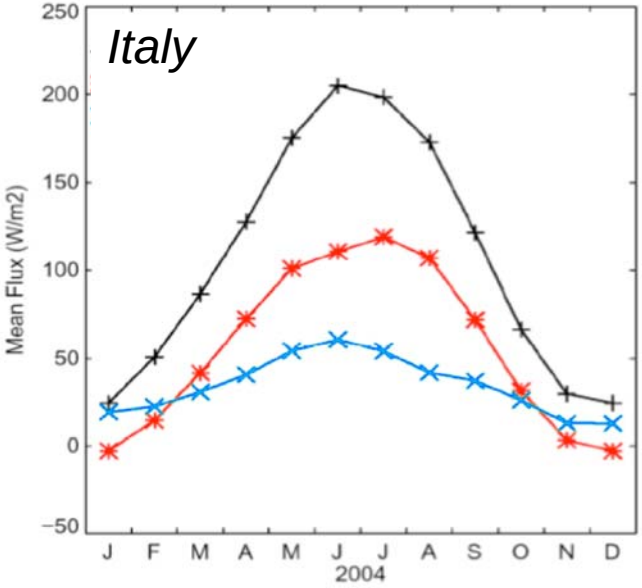
(Guo et al. JHM 2006)

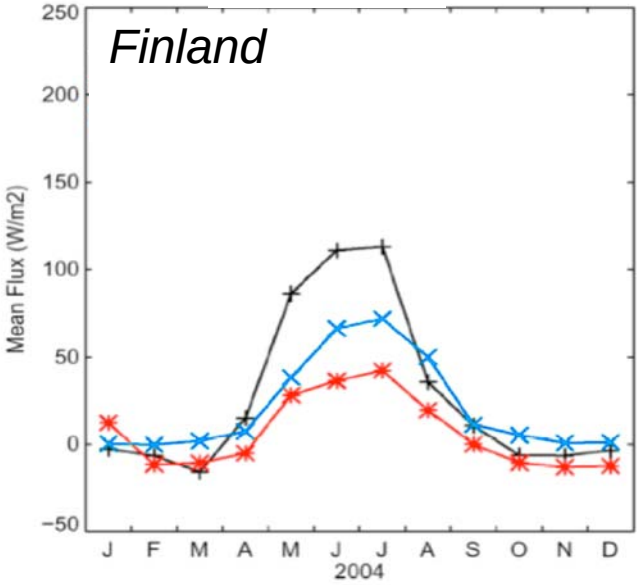
Analysis of Fluxnet sites (ground observations)

Net radiation
Sensible heat flux
Latent heat flux









(Seneviratne and Stöckli, Adv. Glob. Change Res., 2008)

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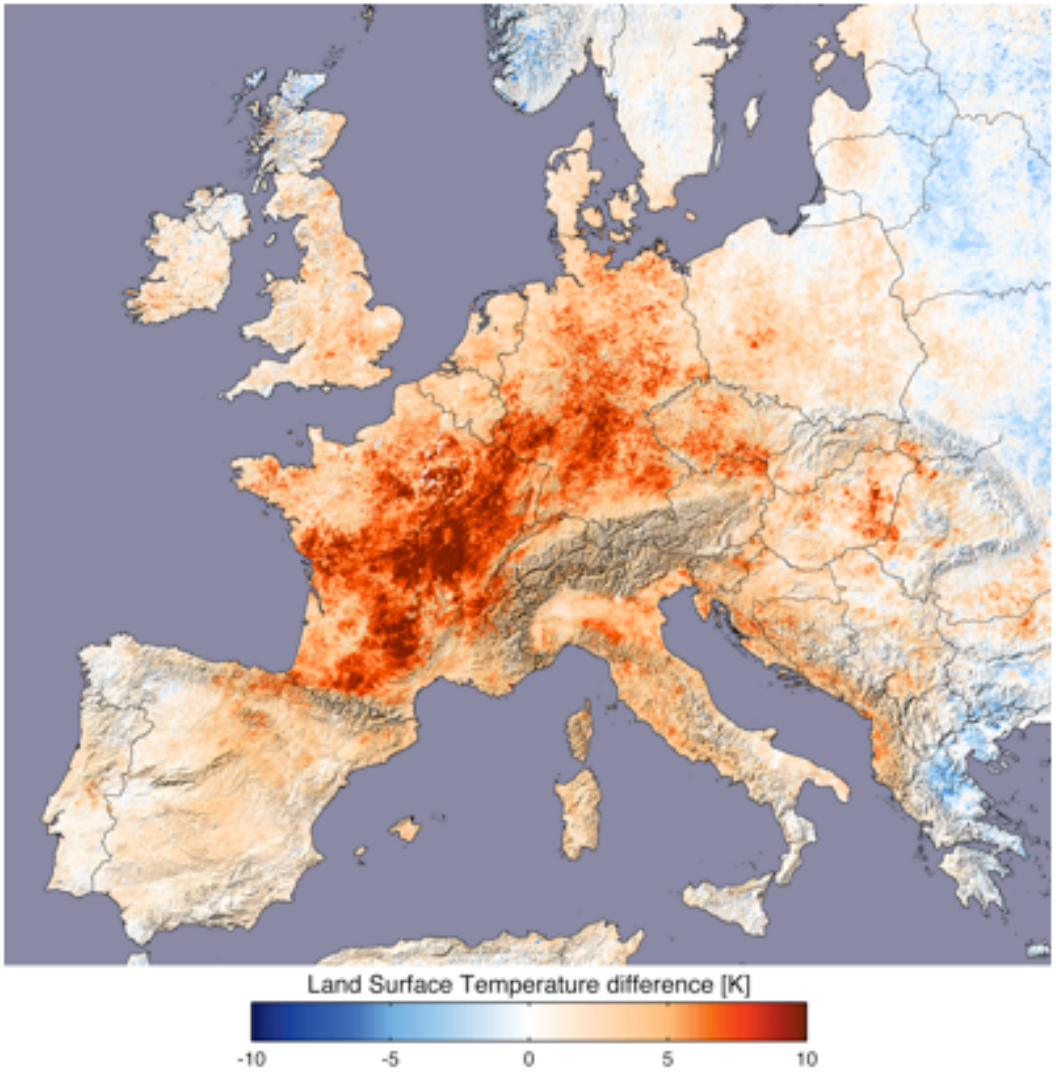
Land-atmosphere coupling and T° variability

More frequent heatwaves in the future in Europe?

What is the role of land-atmosphere coupling?

Doubs River, Switzerland, Summer 2003 (BBC)



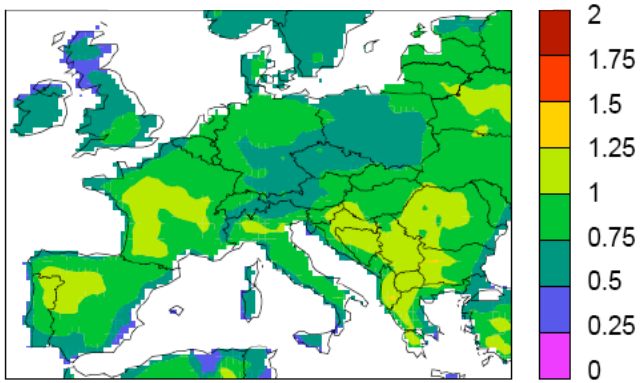
Temperature anomaly, Summer 2003 vs 2000, 2001, 2002, and 2004 (NASA Earth Observatory, Stöckli et al. 2004)

Climate-change feedbacks: Impact on T° variability

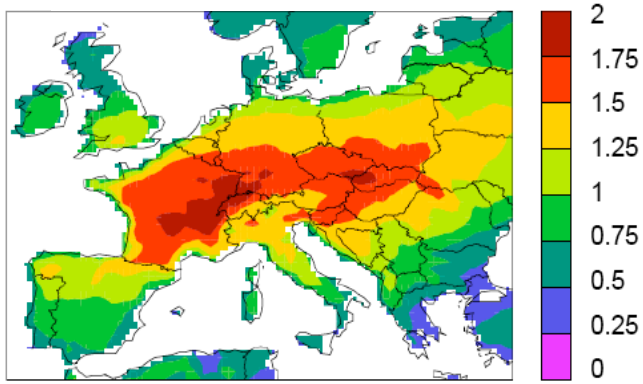
Changes in interannual variability of summer temperature

(Standard deviation of the summer (JJA) temperature)

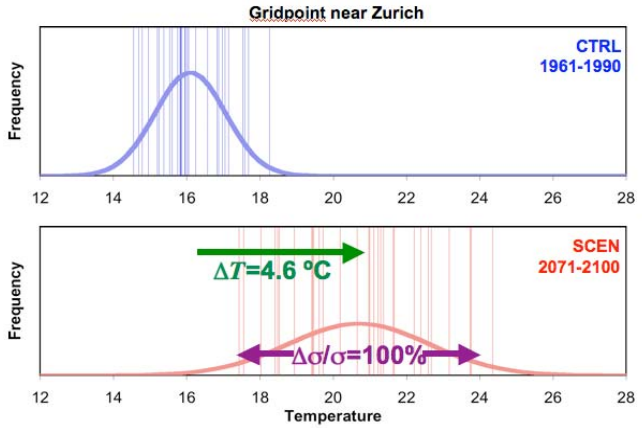
CTL (1970-1989)



SCEN (2080-2099)



(Seneviratne et al. 2006, Nature)



(Schär et al. 2004, Nature)

Climate-change feedbacks: Impact on T° variability

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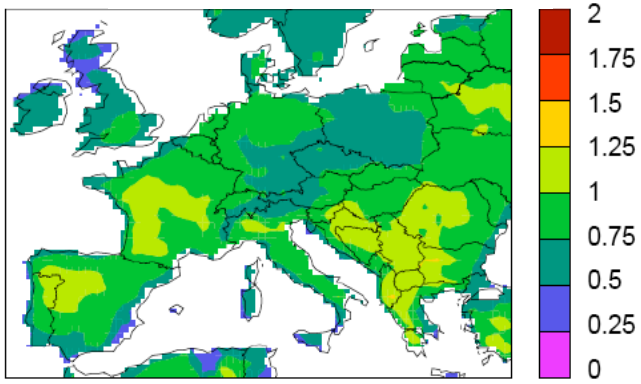

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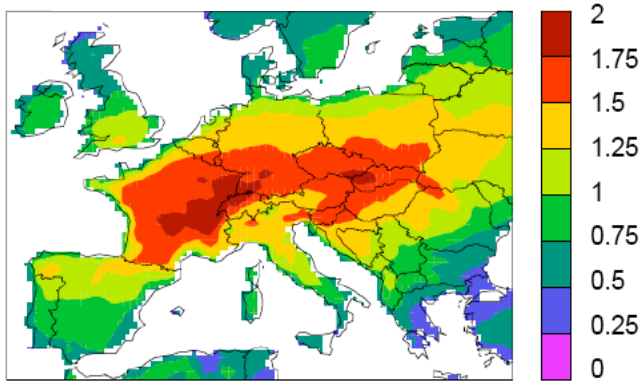
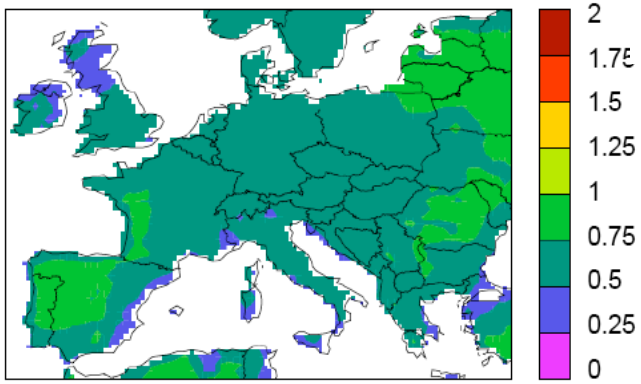
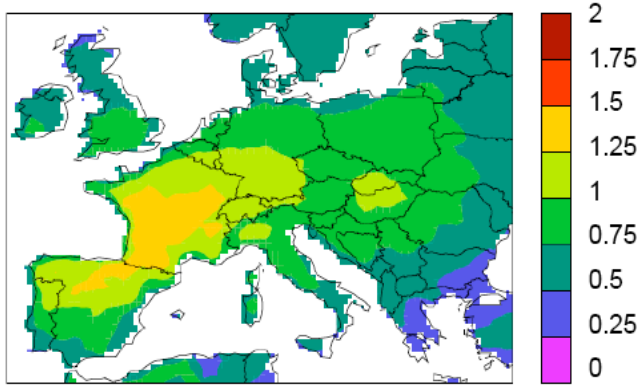


$CTL_{UNCOUPLED}$



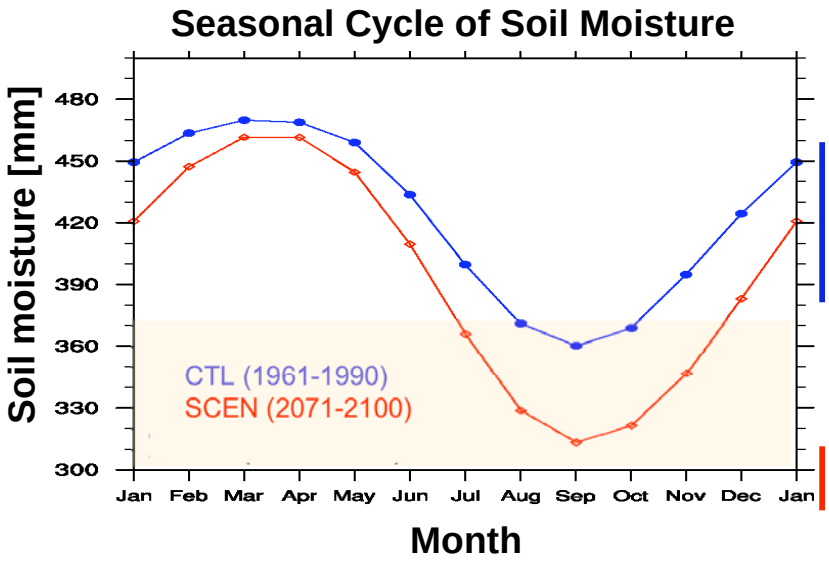
$SCEN_{UNCOUPLED}$



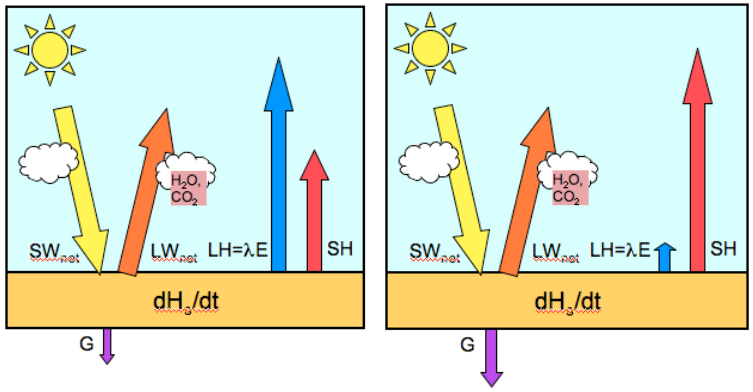
(Seneviratne et al. 2006, Nature)

Large decrease of T° variability when effect of soil moisture is removed

Mechanism

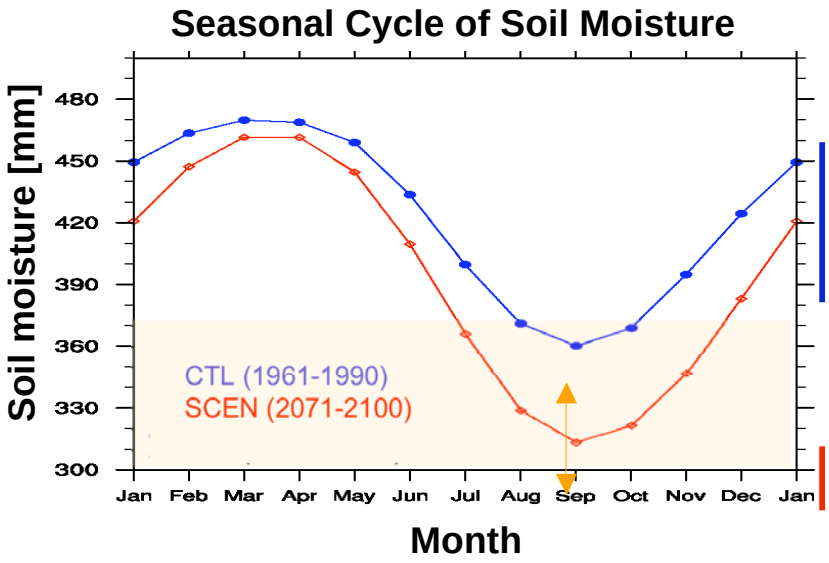


no limitation
wet climate



below threshold
(“plant wilting point”)
dry climate

Mechanism



no limitation
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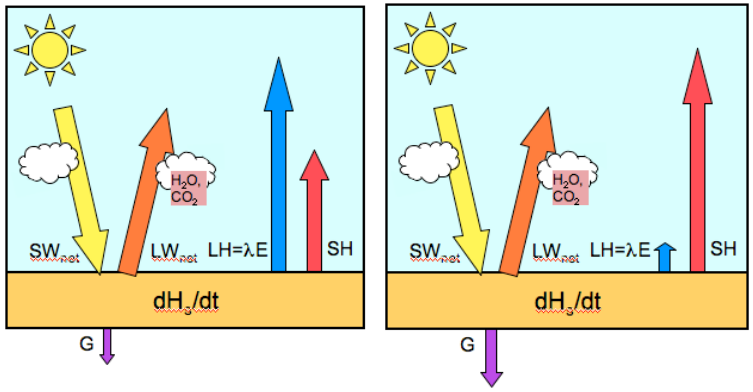
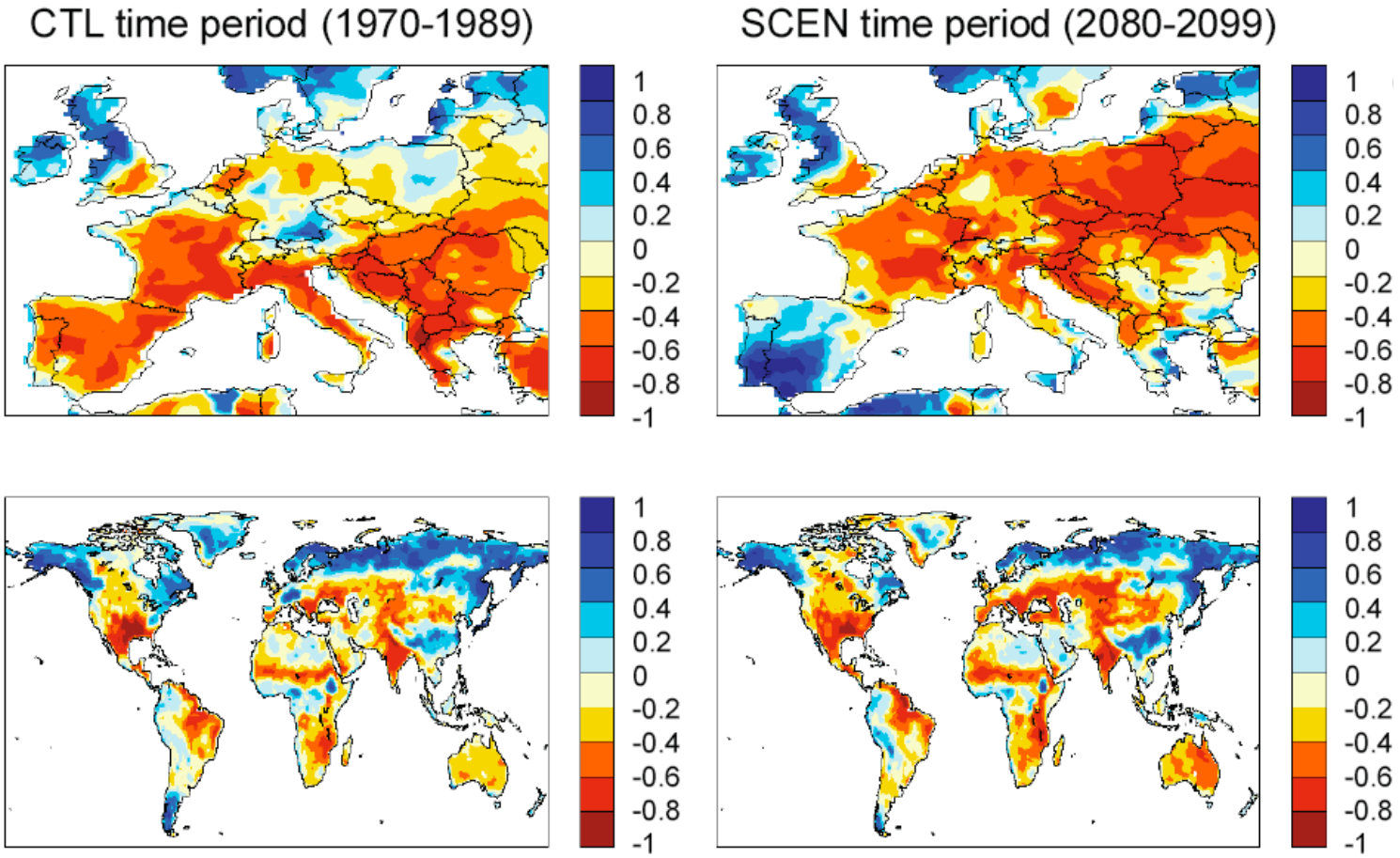


transitional climate

below threshold ("plant wilting point")
dry climate

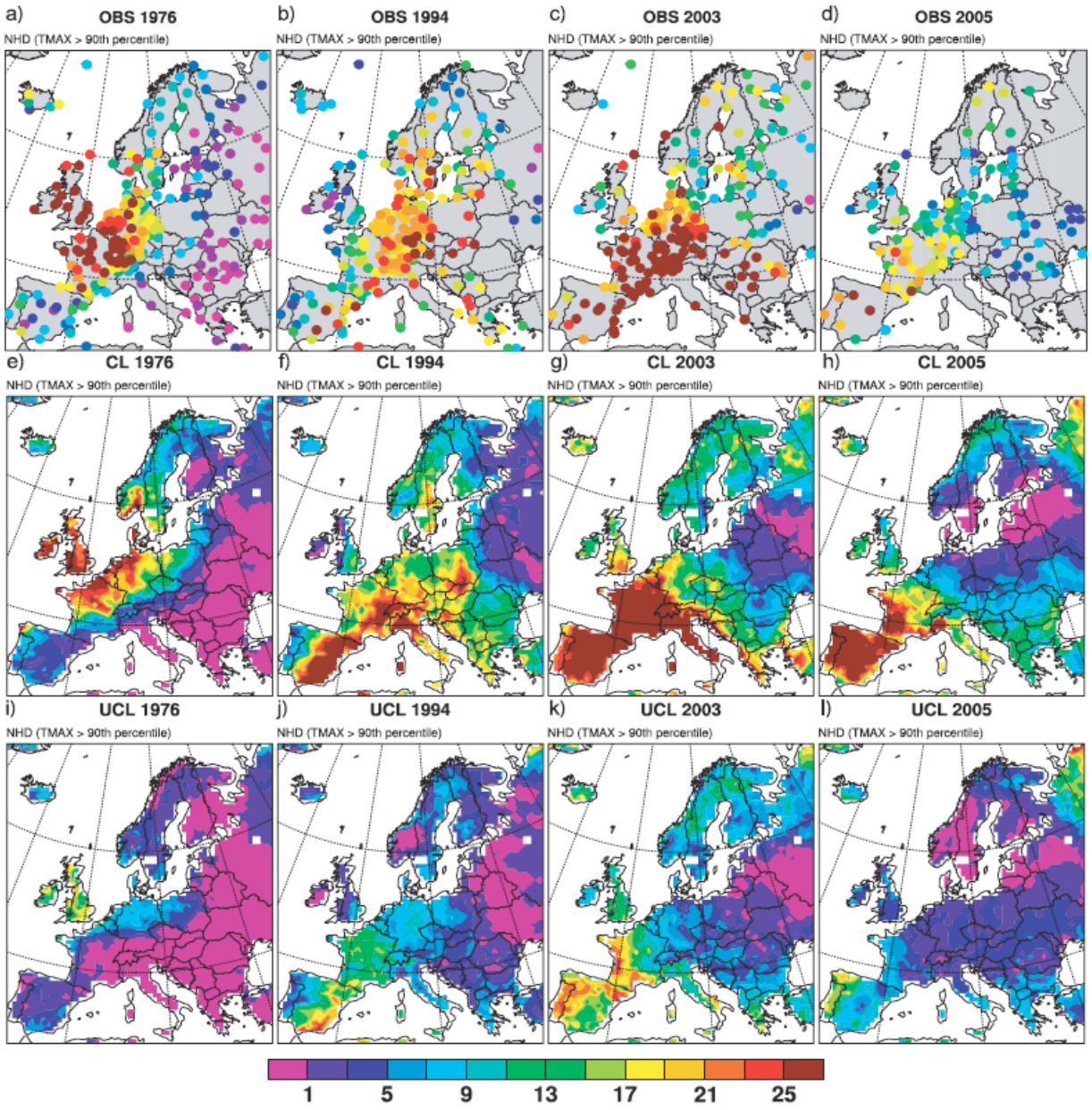
Shift of “hot spots” of soil moisture-temperature coupling

(correlation between temperature and evapotranspiration, CHRM & 3 IPCC models)



(Seneviratne et al. 2006, Nature)

Effects for recent heatwaves



Number of hot days (> 90%ile)

Observations

Reference simulations

With soil moisture climatology

(Fischer et al. 2007, GRL)

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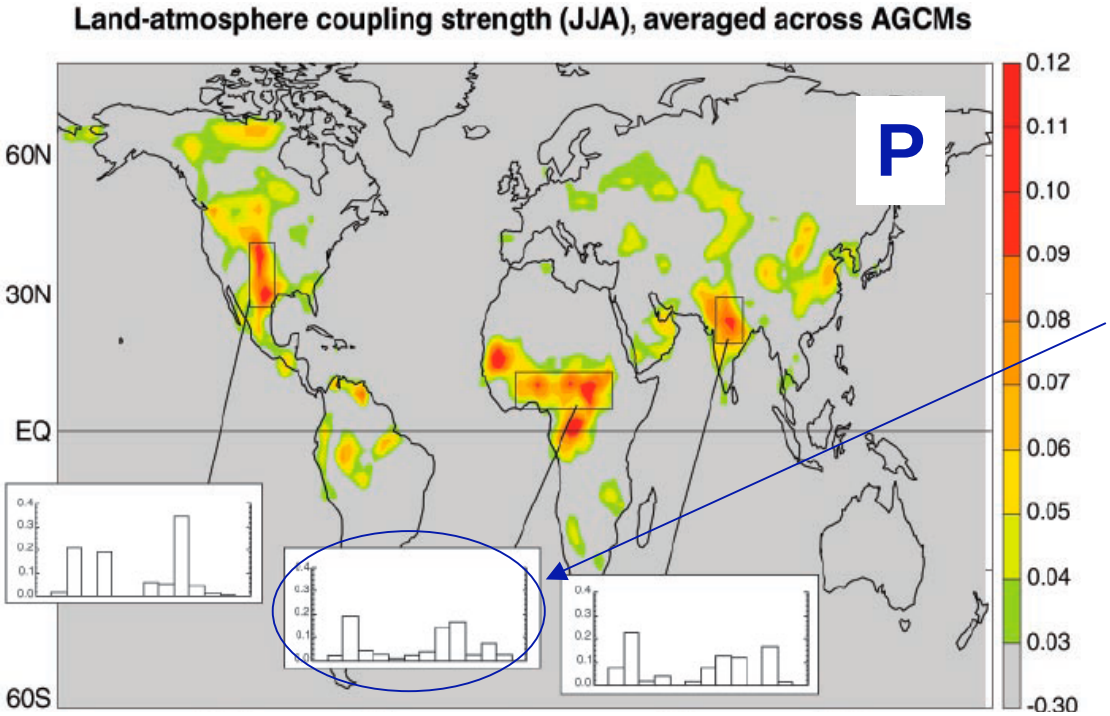
Discussion: Modelling & Observation issues

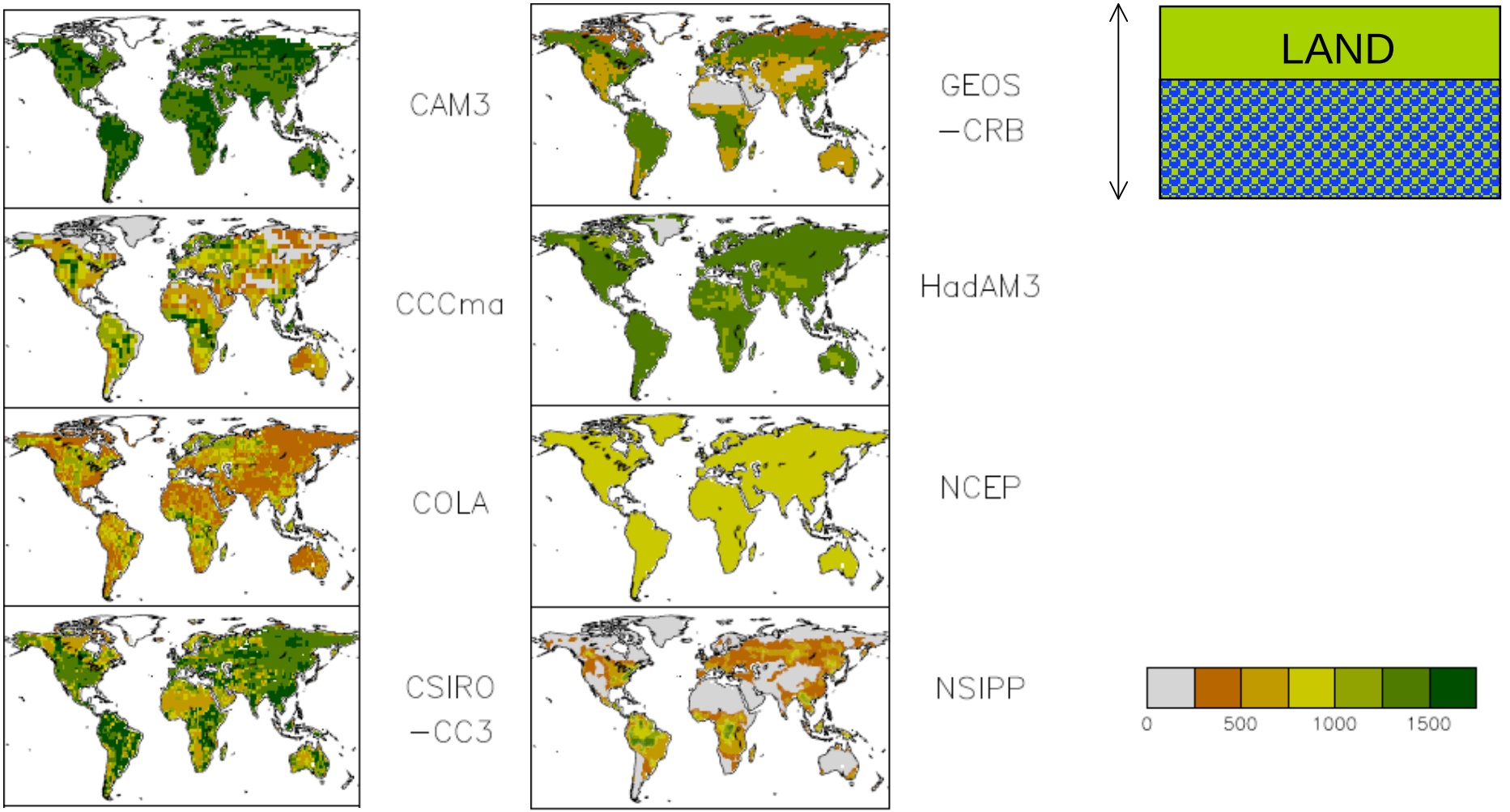
Some **significant uncertainties remain** in the assessment of land-atmosphere interactions and their representation in climate models



Significant range in model behaviour…

(Koster et al. 2004, Science)

Water-holding capacity



(Seneviratne et al. 2006, JHM)

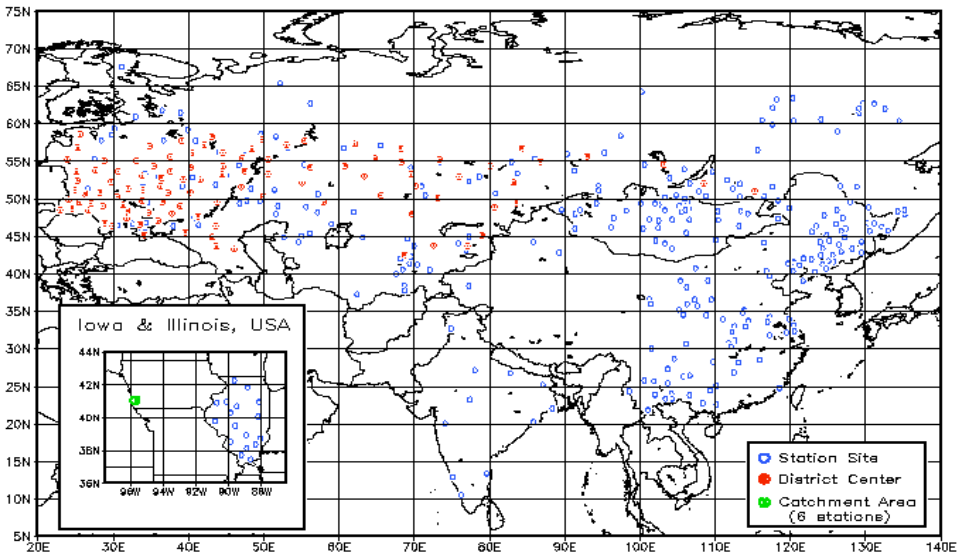
Discussion: Modelling & Observation issues

Can we validate some of the inferred land-atmosphere coupling relationships directly or indirectly?

Observations: Soil moisture / FLUXNET

Soil moisture observations

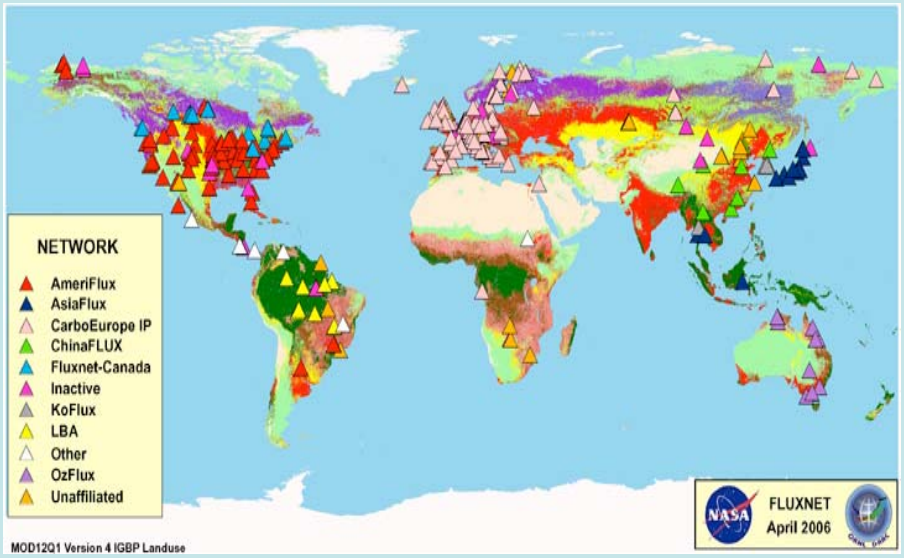
Some long-term measurement networks but many areas without observations, and some measurements were discontinued



Global Soil Moisture Data Bank
(Robock et al. 2000, Bull. Am. Met. Soc.)

Fluxnet stations

Good coverage in North America, Europe and parts of Asia, but many areas not covered, and few soil moisture measurements



http://www-eosdis.ornl.gov/FLUXNET/

Indirect measurements/estimates

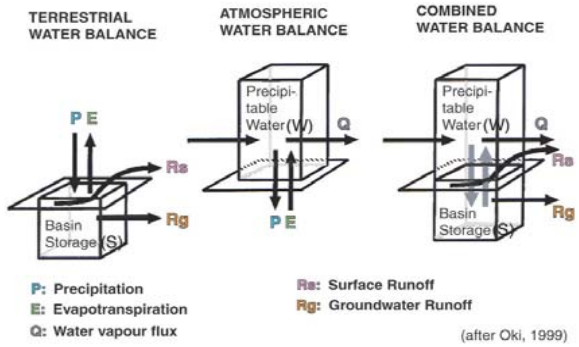
Satellite measurements

- Microwave remote sensing
- GRACE (Gravity Recovery and Climate Experiment)
- NDVI (Normalized Difference Vegetation Index)

GRACE twin satellites

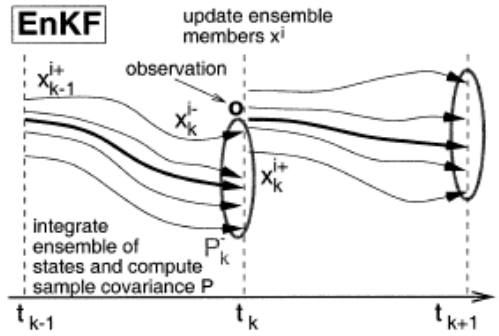
Atmospheric water-balance estimates

- (Seneviratne et al. 2004, J. Climate;
  Hirschi et al. 2006, JHM;
  http://iacweb.ethz.ch/data/water_balance/)



Land surface models with obs. input

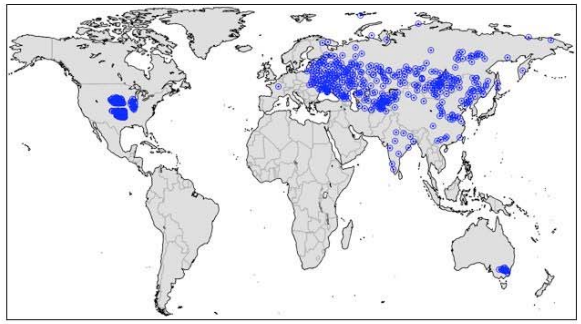
- Global Soil Wetness Project (GSWP)
- Global Land Data Assimilation (GLDAS)
- Land data assimilation with Ensemble Kalman Filter



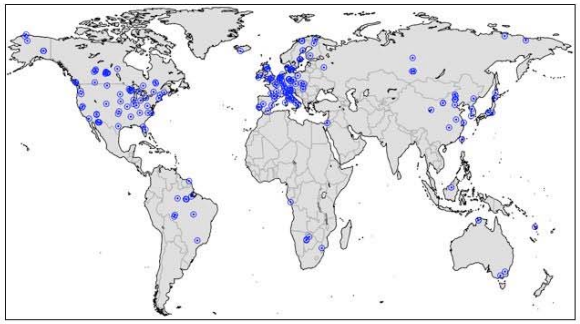
(Reichle et al. 2002, JHM)

Observational datasets

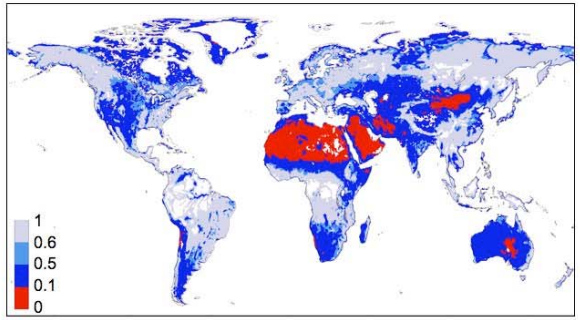
(a) Global Soil Moisture Data Bank



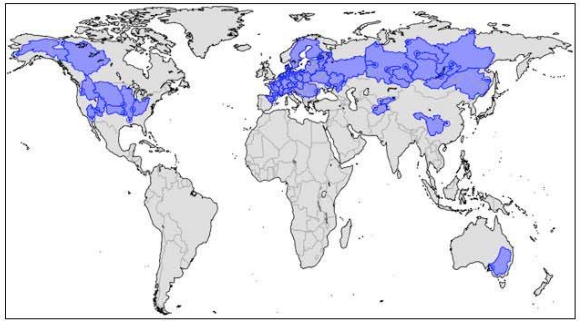
(b) FLUXNET LaThuile Synthesis Dataset



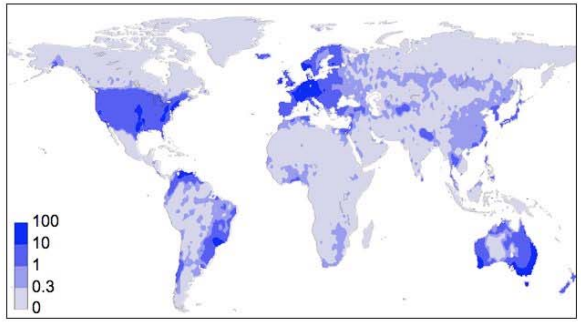
(c) Vegetation densities (microwave RS)



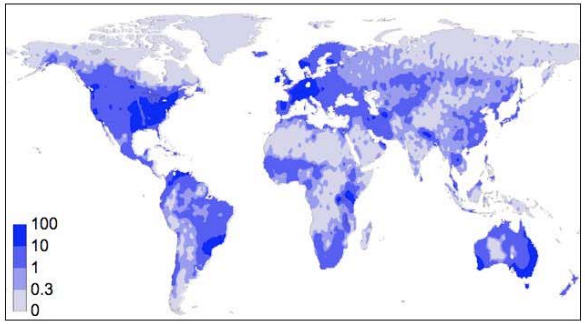
(d) Basin-Scale Water Balance Dataset



(e) Number of GPCC Rain Gauges (Min)



(f) Number of GPCC Rain Gauges (Max)



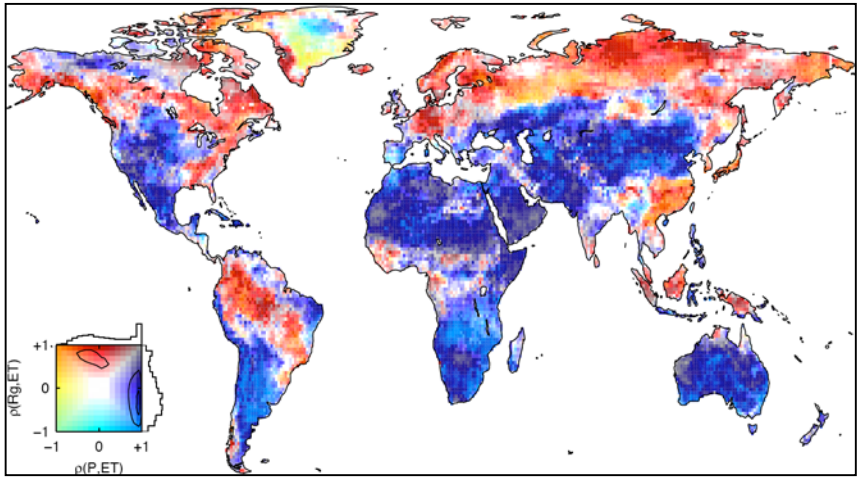
(Seneviratne et al. 2009, in prep)

Discussion: Modelling & Observation issues

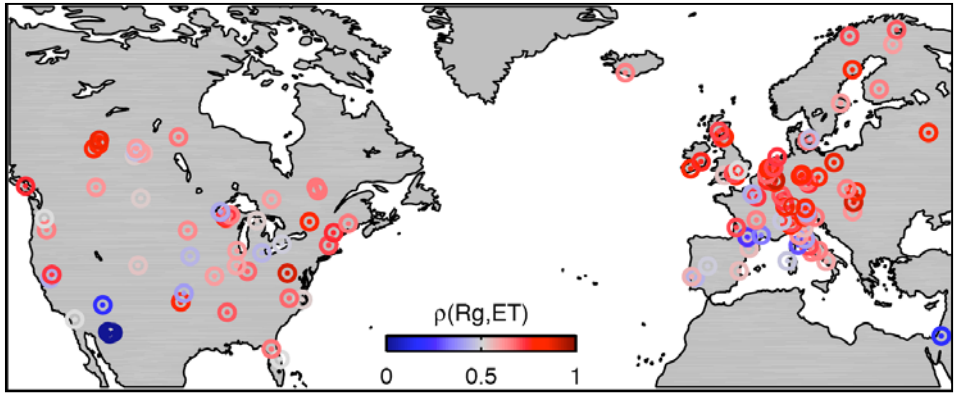
What can we learn with these datasets?

Potential of new land surface datasets

e.g. Identify soil moisture and radiation-limited regimes



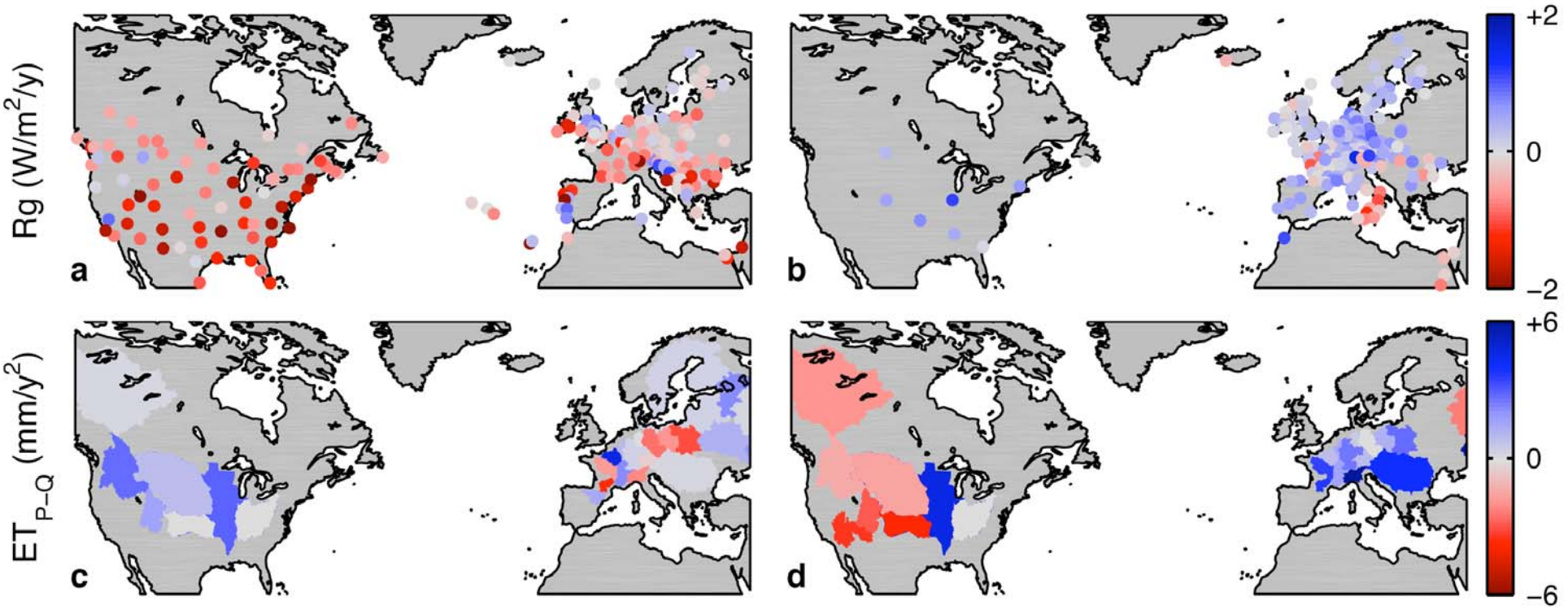
GSWP data



Fluxnet data

(Teuling et al. 2009, GRL)

ET / Dimming and brightening



Trends during the dimming (1958-1982) and brightening (1983-2006) phases

(Teuling et al. 2009, GRL)

Summary: Validation

- **Models do often not agree wrt to land-atmosphere coupling characteristics:**
  - Some general (qualitative) relationships can be derived
  - But for more detailed (quantitative) assessments, the models do show a wide variety of sensitivity

- **One needs to make better use of existing observations:**
  - Define new diagnostics for the assessment of climate and land models
  - “Merge” existing observations (land data assimilation)

- **⇒ Strong potential of FLUXNET data for such efforts (also in combination with other observational datasets)**

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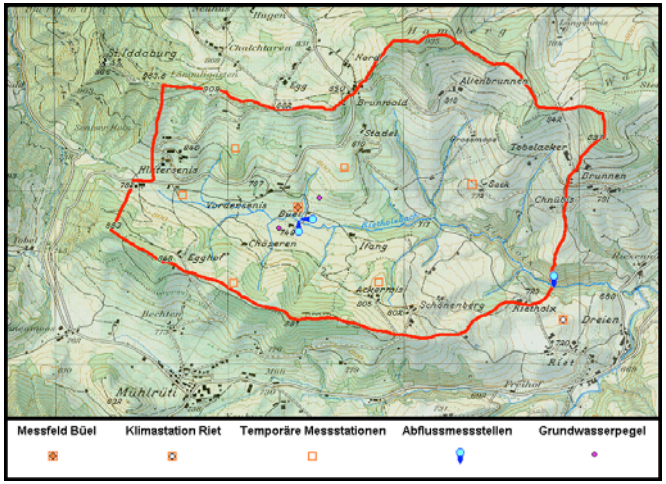
Conclusions

Land-atmosphere interactions play a key role within the climate system:

- Important link between the **energy, water and carbon cycles**
- **Memory** component (storage)
- Induce **critical thresholds** in the climate system
- **Relevant for climate variability and extreme events**
- **Affected by global warming AND key player of climate change**

FLUXNET data can play a key role in furthering our understanding of the relevant processes and reduce model uncertainty

Rietholzbach site: Overview

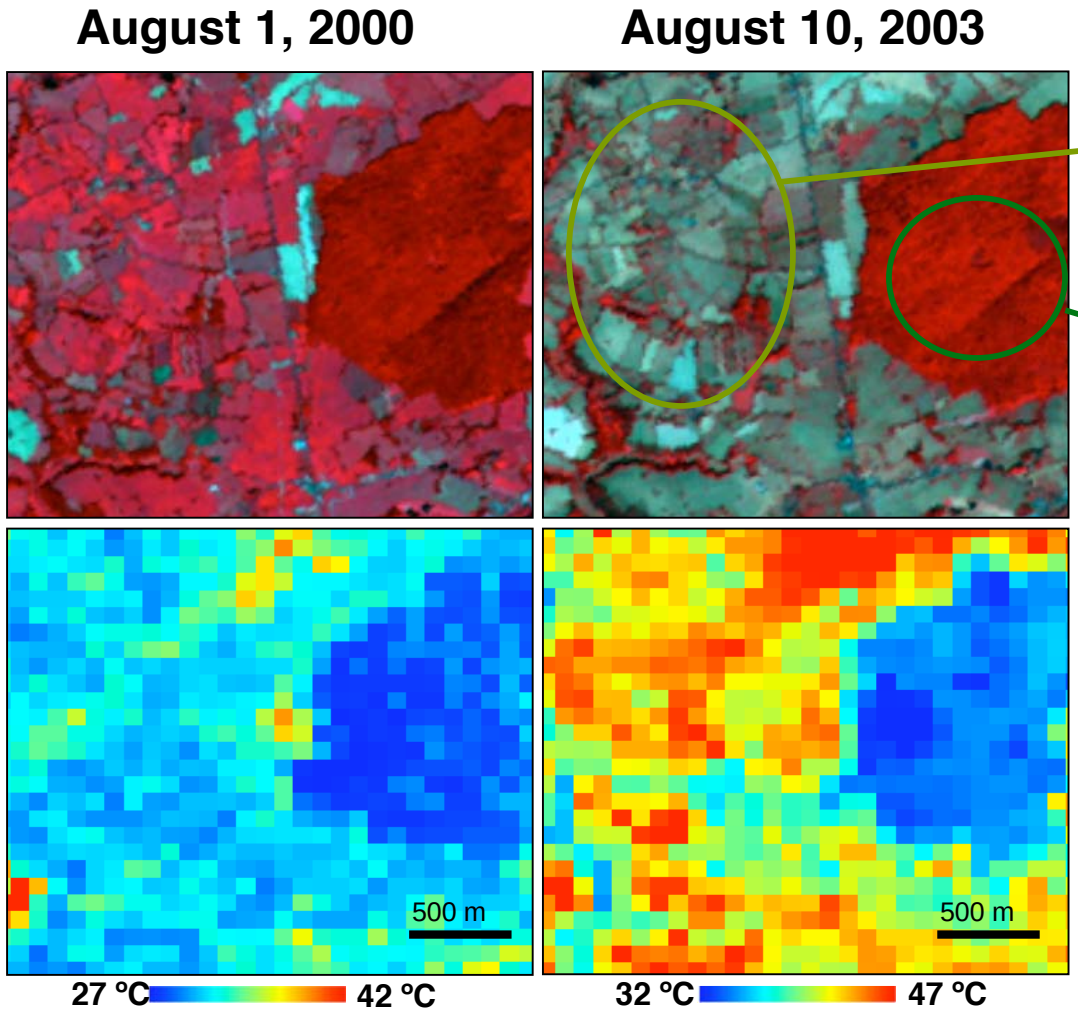


- Research catchment
- Measurements since 1975 (32-year timeseries)
- **Evapotranspiration (lysimeter, water probes for isotope analyses)**, runoff, meteorological variables, radiation (since 1994), soil moisture (since 1994)

- Since 2007 part of the Land-Climate Interactions group
- Current plans: **Eddy-covariance measurements**, enhanced spatial sampling of soil moisture
- Management of the site: Dr. Irene Lehner; Instrumentation: Karl Schroff
- Overview paper in preparation

Land-atmosphere coupling: Role of vegetation

Impact of vegetation cover (example for 2003 heatwave)



Aster Satellite (NASA/Japan)

5x5 km view in Central France

(Zaitchik et al. 2006, Int. J. Clim.)

SwissSMEX: Swiss Soil Moisture Experiment (2008-2011; SNF)

ETH Zurich, IAC: S.I. Seneviratne (PI), H. Mittelbach, I. Lehner, A.J. Teuling, K. Schroff
Agroscope ART: J. Fuhrer (co-PI), C. Ammann
MeteoSwiss: M. Rotach (co-PI), Y-A. Roulet






Land surface models with observation-based forcing

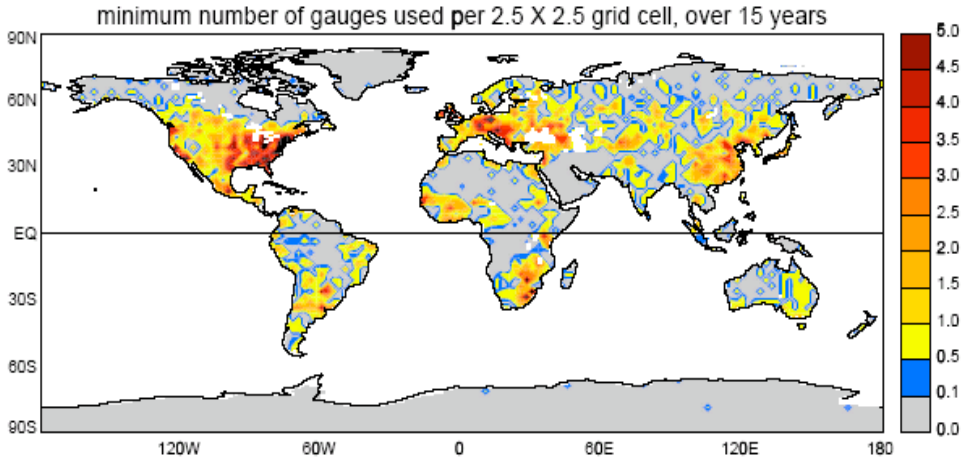
e.g. Global Soil Wetness Project-2 (GSWP-2; http://www.iges.org/gswp/)
Based on several land surface models, for time period 1986-1995

Observation-based forcing (P, rad, ..)

↓

Land surface model

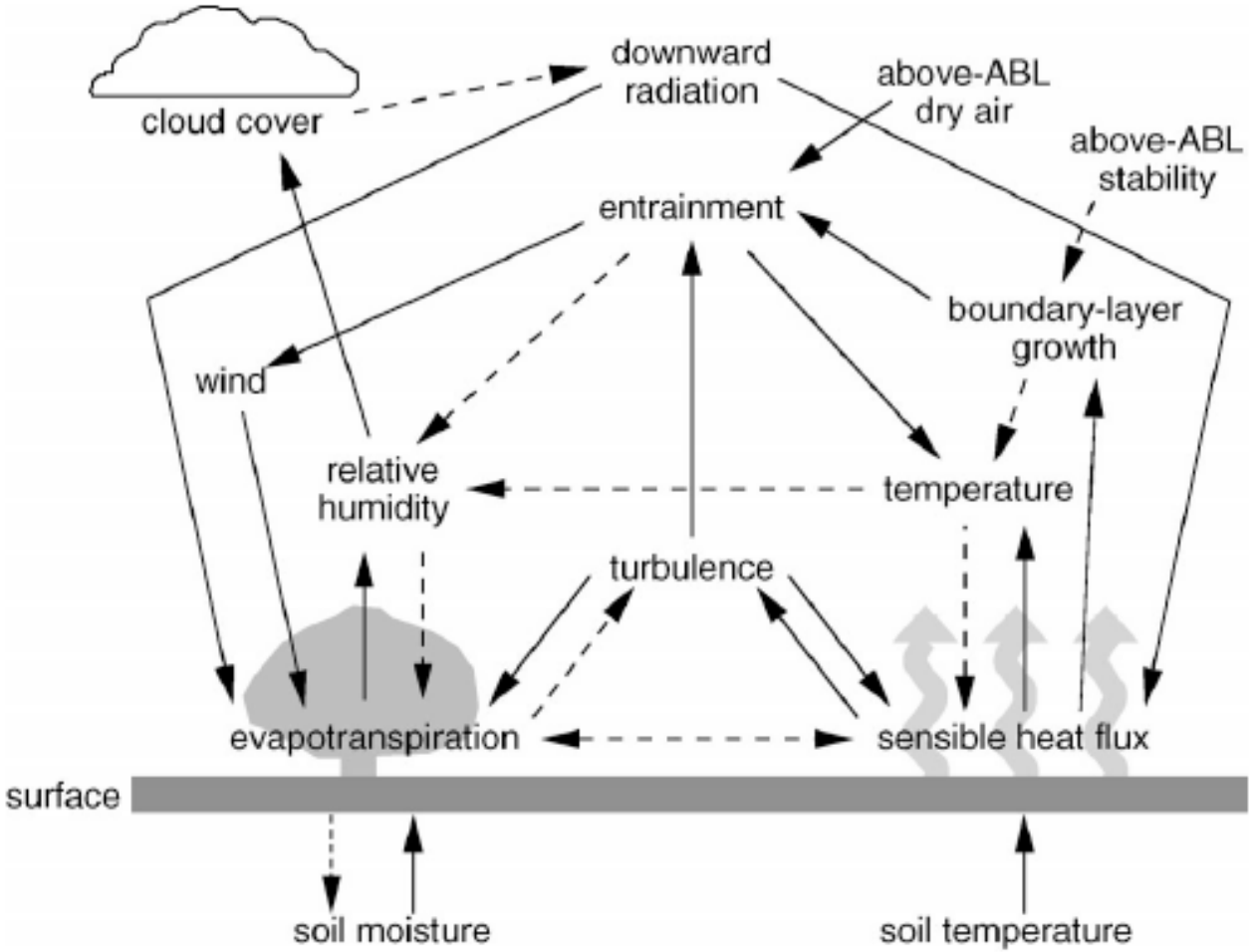
→ Soil moisture, evapotranspiration, surface temperature, sensible heat flux, ...



Oki et al 1999: a minimum of about 30 precipitation gauges per 10^6 km^2 or about 2 gauges per 2.5º x 2.5º GPCP grid cell are required for accurate streamflow simulations

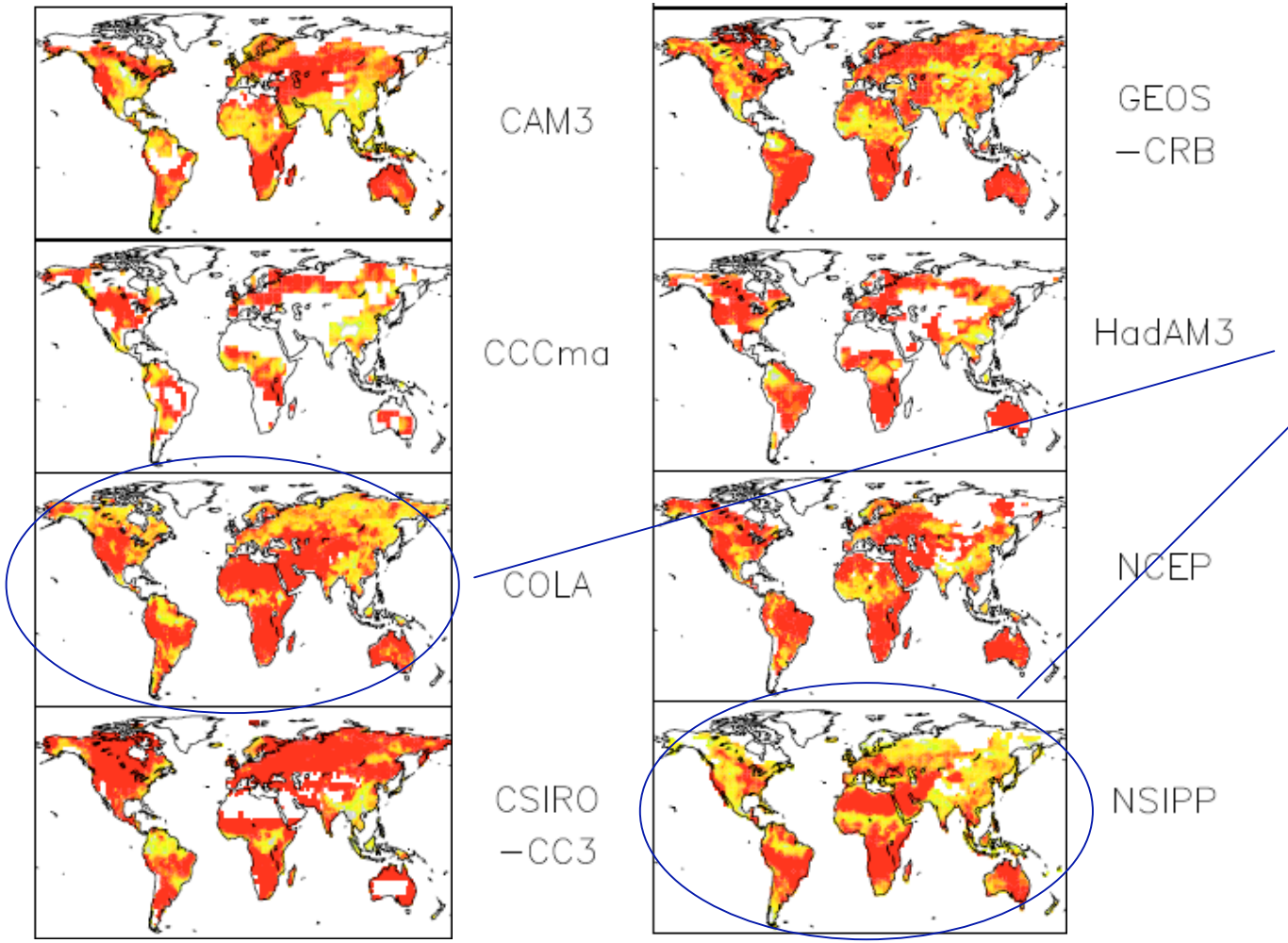
Soil moisture - precipitation feedbacks

NB: Both negative and positive feedbacks may be possible



(Ek and Holtslag 2004, JHM)

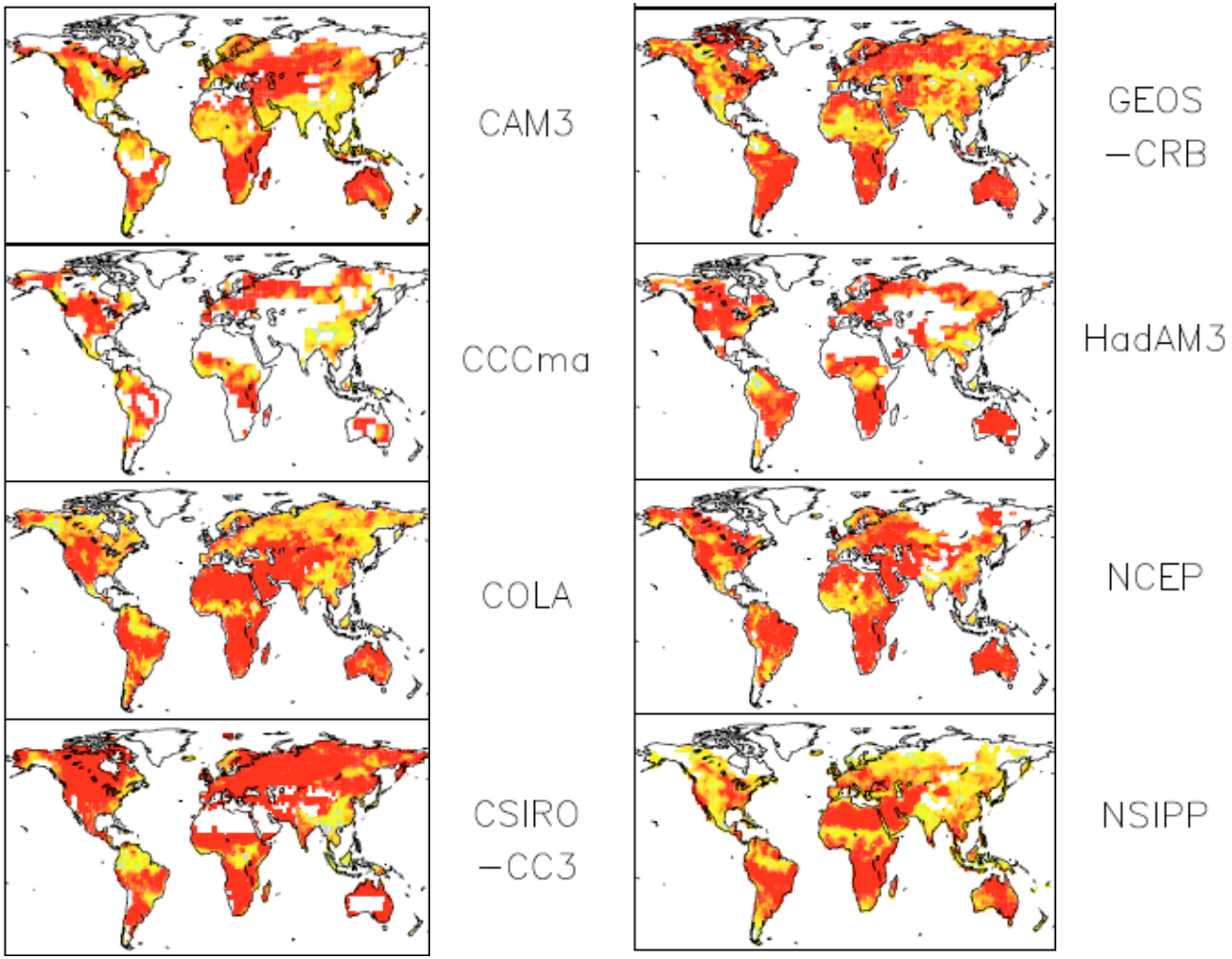
Soil moisture memory



Some differences in soil moisture memory can be linked to differences in water-holding capacity…

(Seneviratne et al. 2006, JHM)

Soil moisture memory



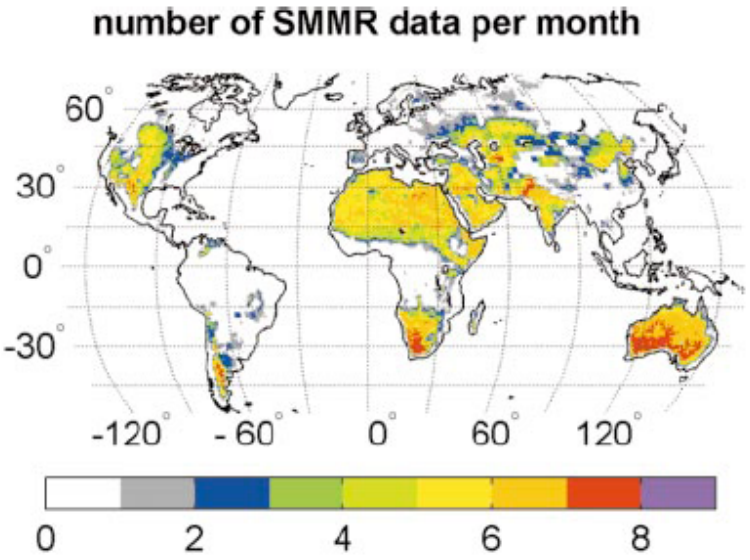
(Seneviratne et al. 2006, JHM)

Satellite measurements

Microwave remote sensing

Issues:

- measurements not possible under dense vegetation cover
- measures only top few cm of soil (no information on root zone soil moisture)



(Reichle et al. 2004, JHM)

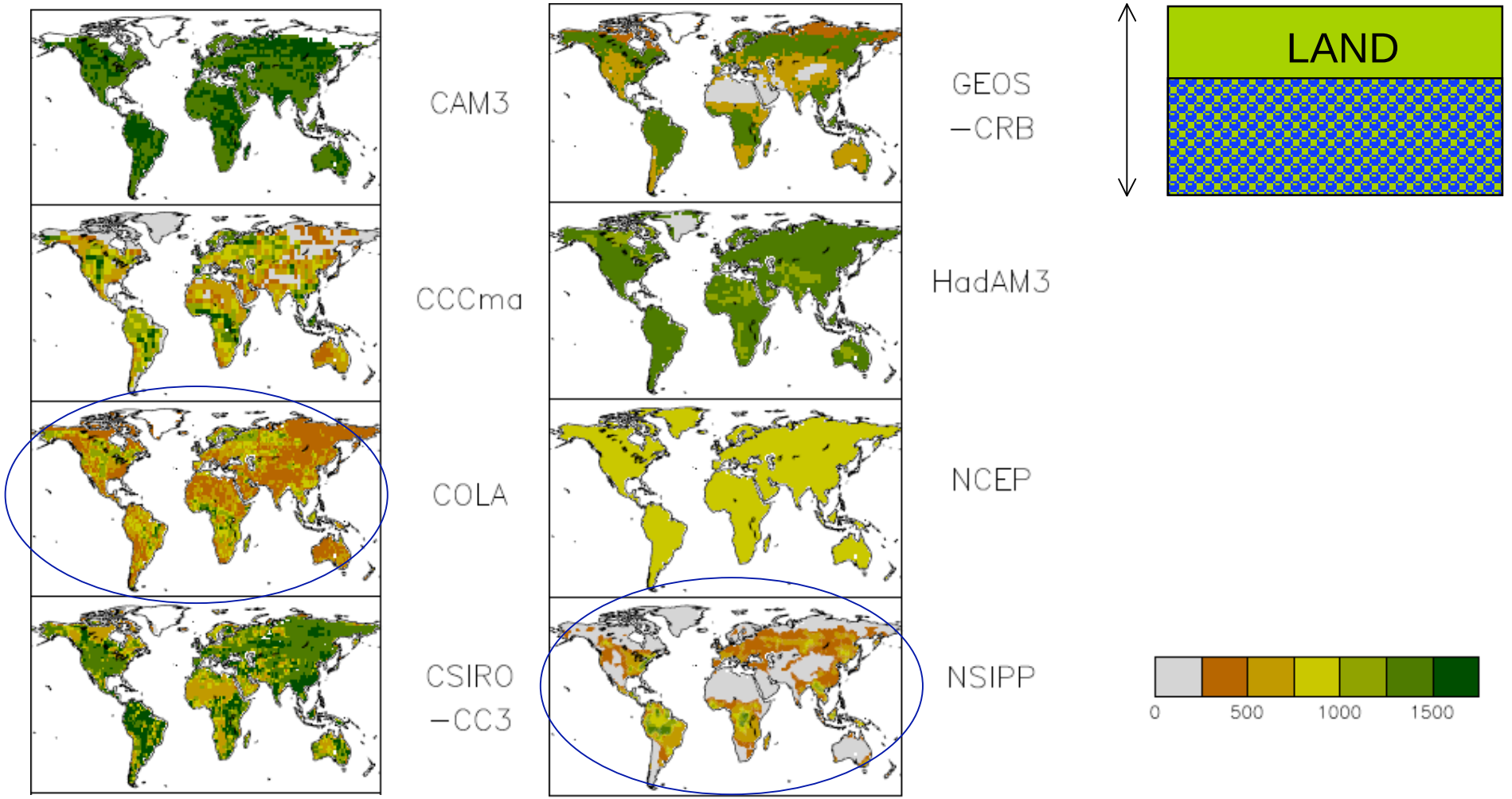
Gravity Recovery and Climate experiment

Issues:

- coarse resolution (500-1000km)
- measures whole terrestrial water storage (soil moisture, groundwater, snow)

GRACE twin satellites

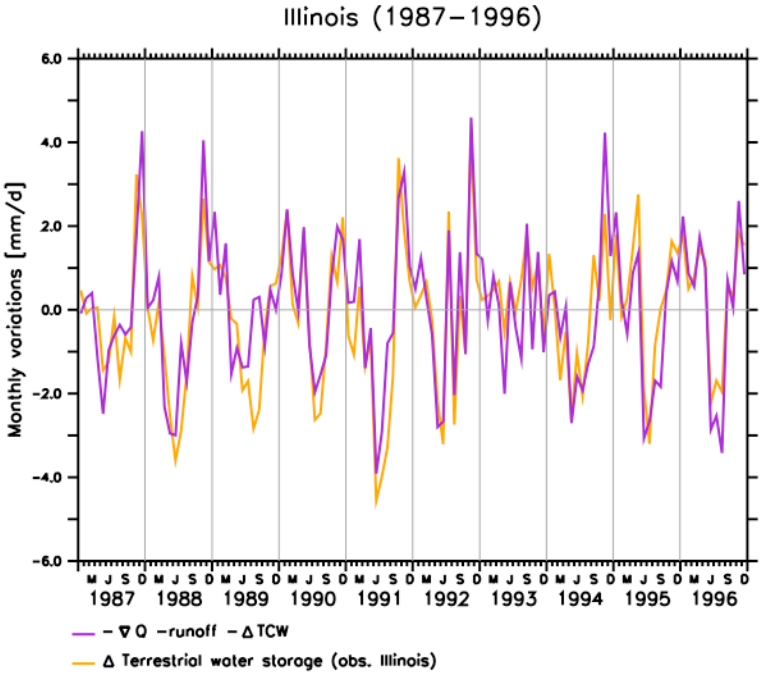
Water-holding capacity



(Seneviratne et al. 2006, JHM)

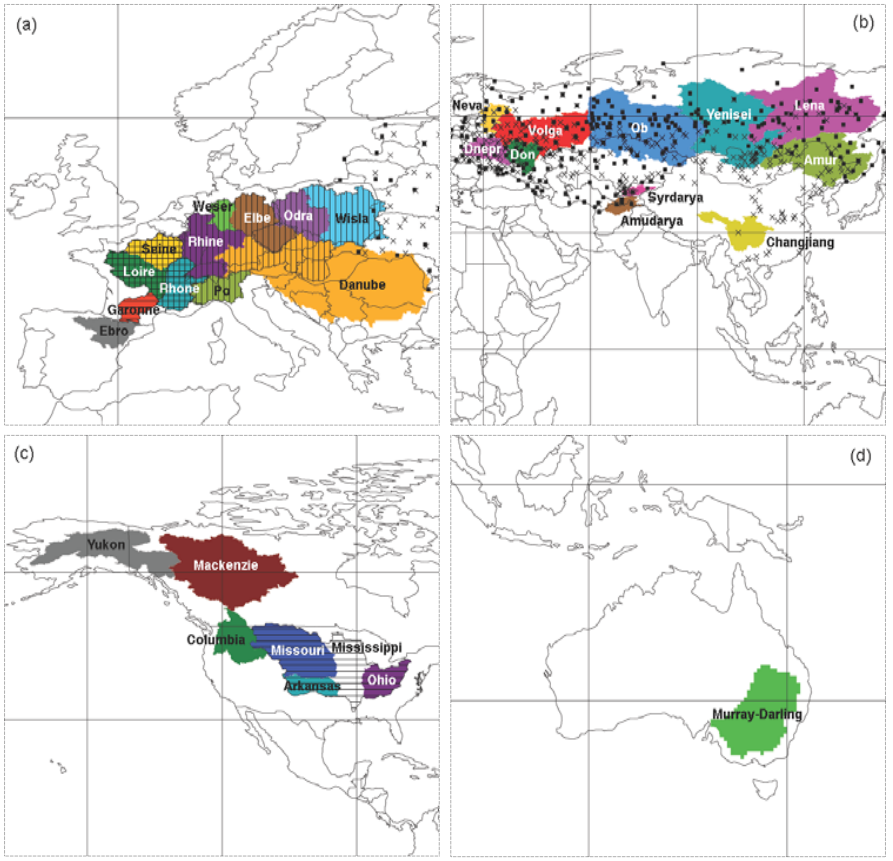
Basin-Scale Water Balance estimates

$$\frac{\partial S}{\partial t} = -\nabla_H \vec{Q} - \frac{\partial W}{\partial t} - R$$



(Seneviratne et al., J. Climate, 2004)

http://iacweb.ethz.ch/data/water_balance/



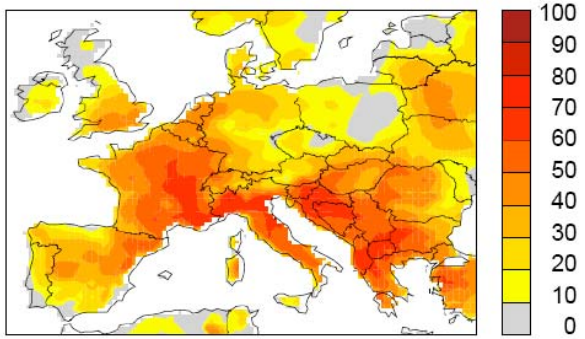
(Hirschi et al., J. Hydrometeorology, 2006)

Issues:

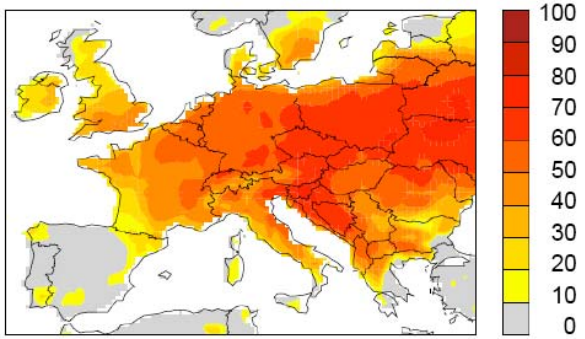
- coarse resolution (300-1000km), whole terrestrial water storage, no trends
- **but retrospective dataset!** (whole reanalysis period)

Climate-change impact on land-atmosphere coupling

σ^2_T: (CTL-CTL$_{UNCOUPLED}$)/CTL [%]



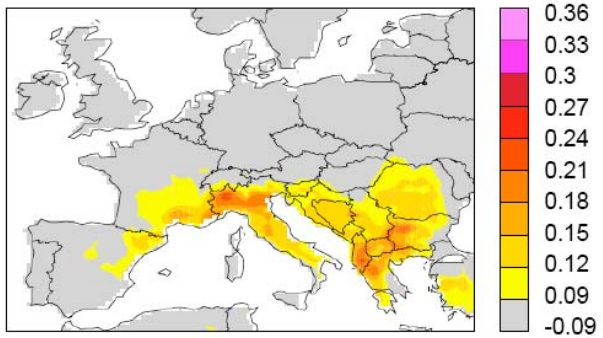
σ^2_T: (SCEN-SCEN$_{UNCOUPLED}$)/SCEN [%]



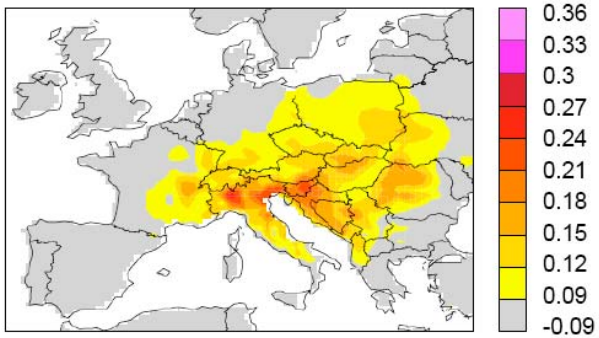
percentage of T^o variance explained by coupling [%]

$$\frac{\sigma^2_{T(COUPLED)} - \sigma^2_{T(UNCOUPLED)}}{\sigma^2_{T(COUPLED)}}$$

Ω_T(CTL$_{UNCOUPLED}$)-Ω_T(CTL)



Ω_T(SCEN$_{UNCOUPLED}$)-Ω_T(SCEN)



land-atmosphere coupling strength parameter analogous to GLACE

- *Shift of region of strong soil moisture-T^o coupling* from the Mediterranean to most of Central and Eastern Europe in future climate ⇒ more temperature variability and future heatwaves in this region

(Seneviratne et al. 2006, Nature)

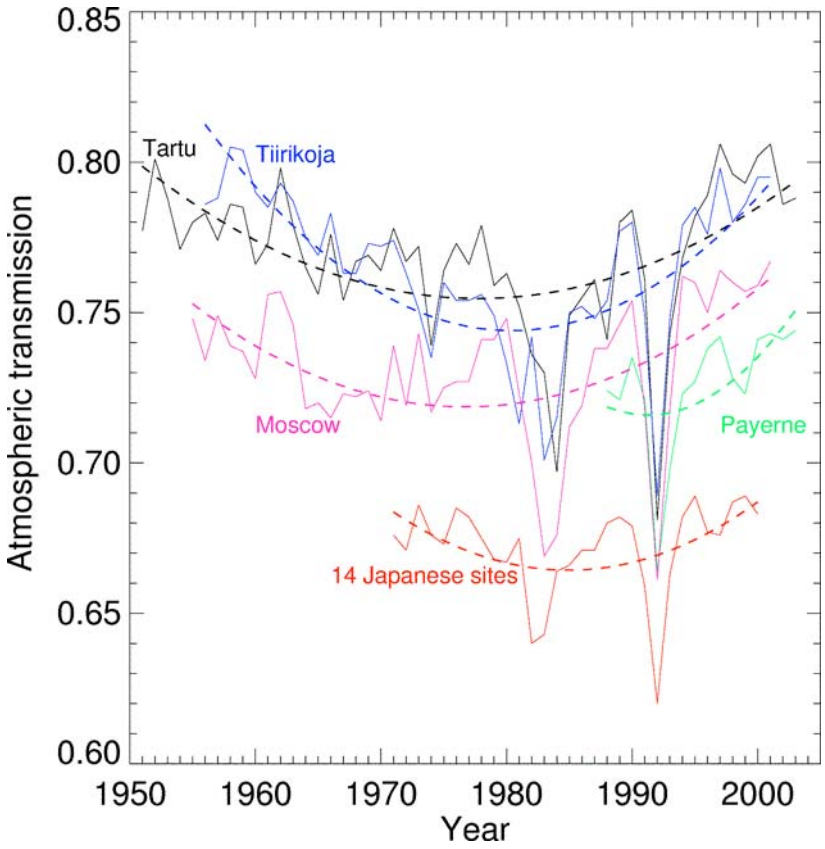
Summary

- **The projected enhancement of T^o variability in Central and Eastern Europe is mostly due to changes in land-atmosphere coupling**

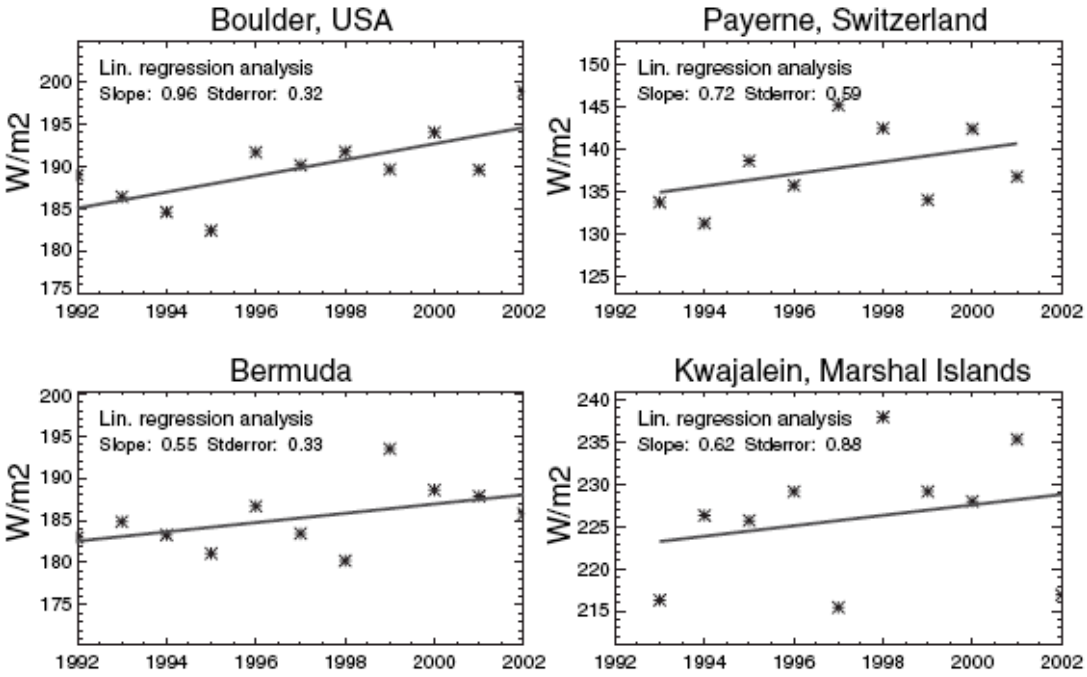
- **Climate change creates a new hot spot of soil moisture - T^o coupling in Central and Eastern Europe in the future climate (shift of transitional climate zone)**

Modifications with climate change

NB: Other modifications are also relevant (e.g. changes in aerosol concentrations)



(Martin Wild, ETH Zurich)



(Wild et al. 2005, Science)

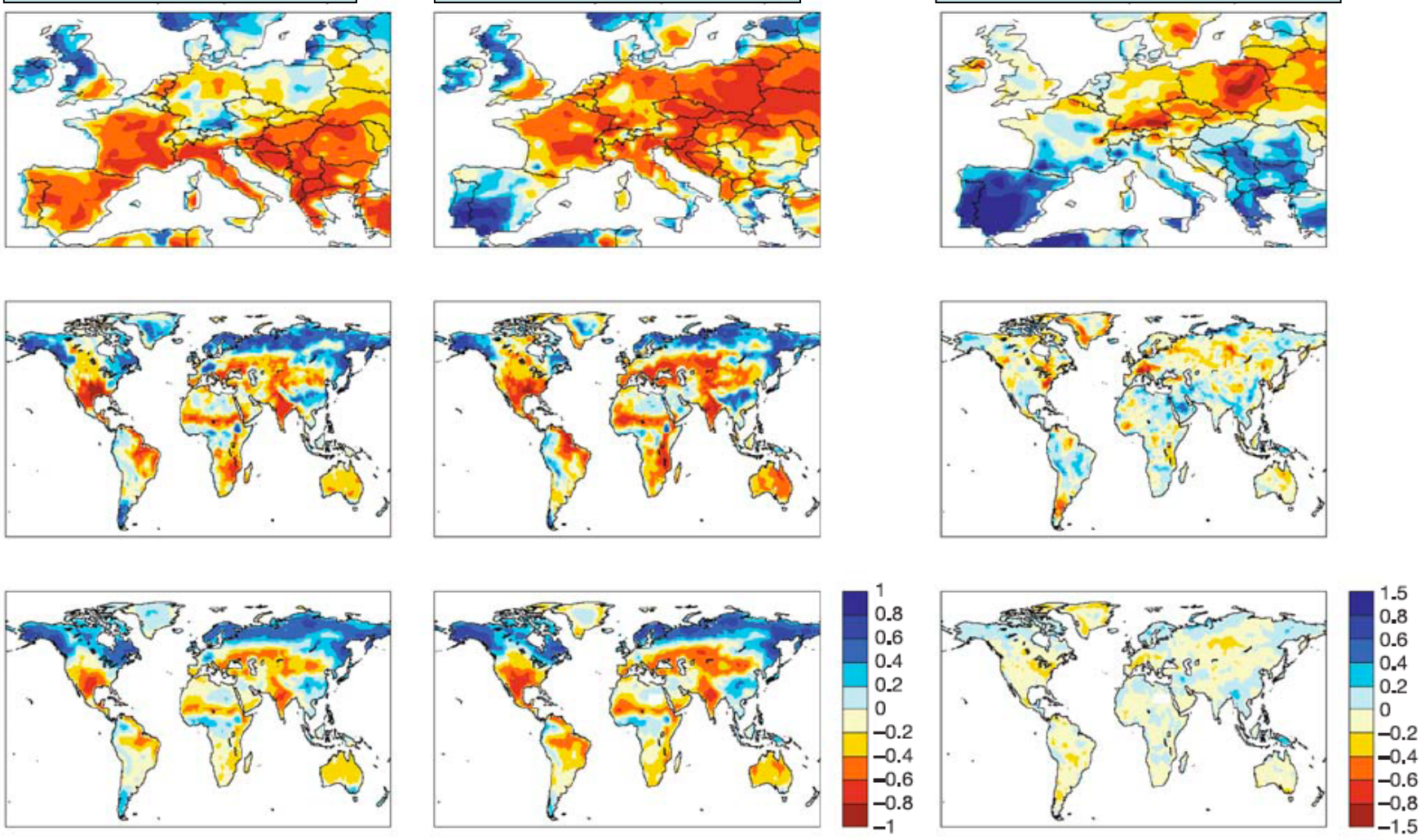
Comparison IPCC AR4 GCMs: $\rho_{(ET,T2M)}$

CTL time period | SCEN time period | Climate-change signal

RCM

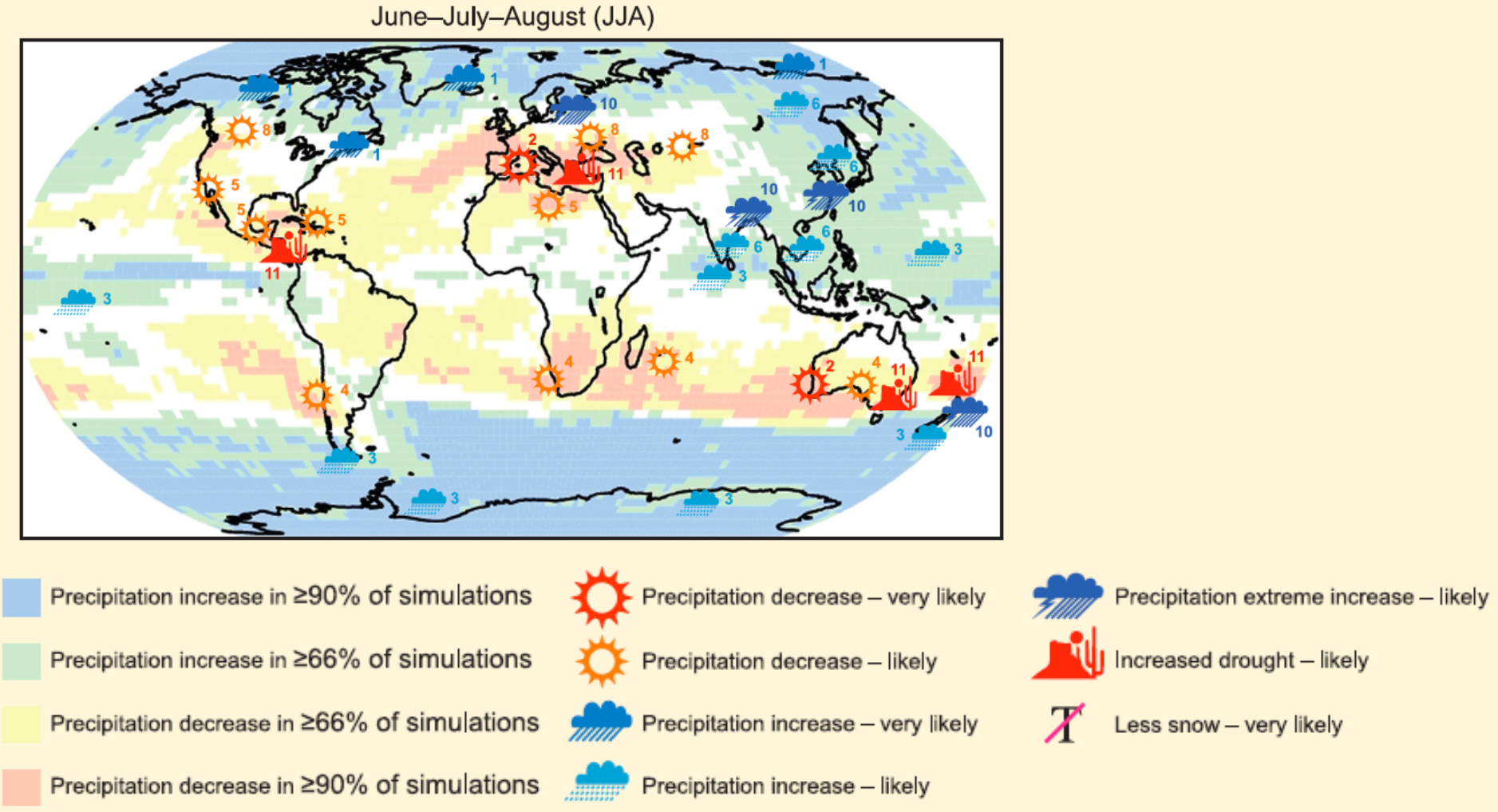
3 “best” GCMs

All GCMs



(Seneviratne et al. 2006, Nature)

Modifications with climate change



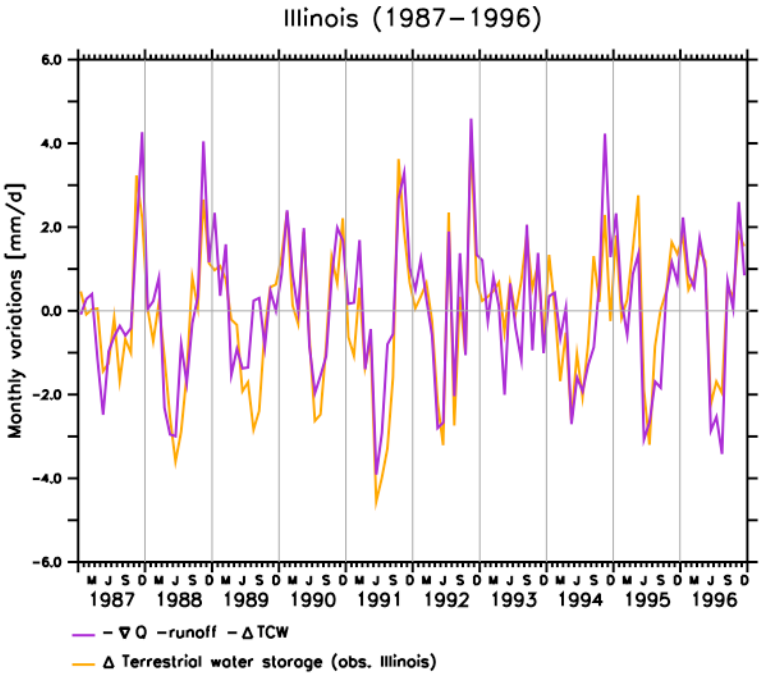
(IPCC 2007)

BSWB estimates

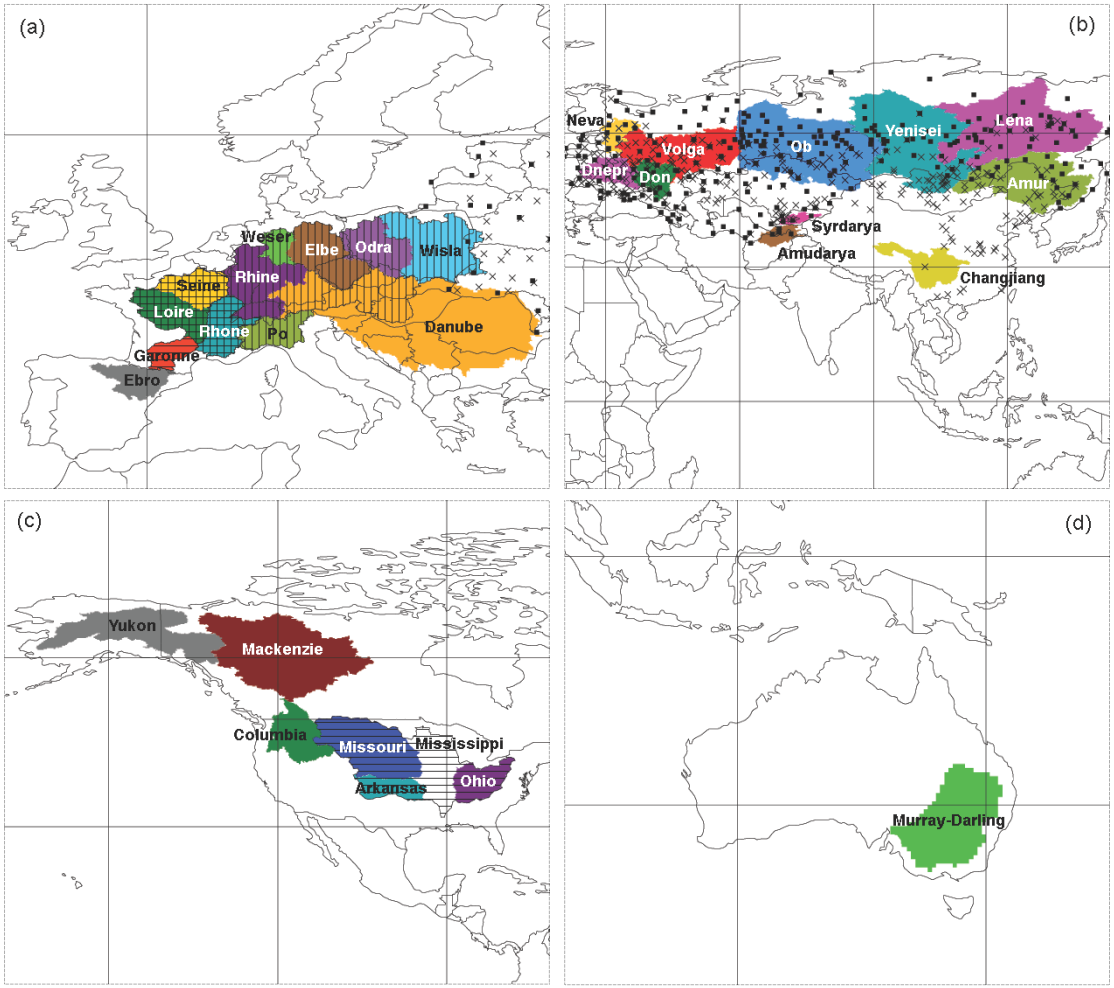
"Basin-Scale Water Balance" estimates

http://iacweb.ethz.ch/data/water_balance/

$$\frac{\partial S}{\partial t} = -\nabla_H \vec{Q} - \frac{\partial W}{\partial t} - R$$



(Seneviratne et al., J. Climate, 2004)

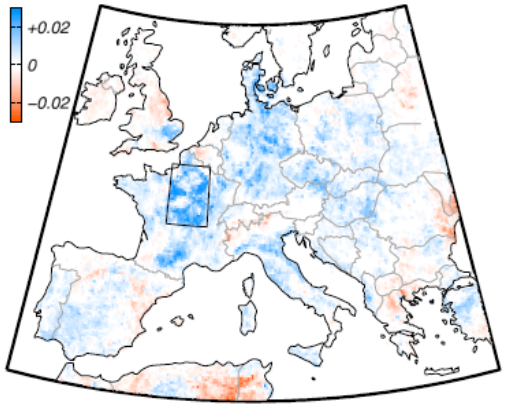


(Hirschi et al., J. Hydrometeorology, 2006)

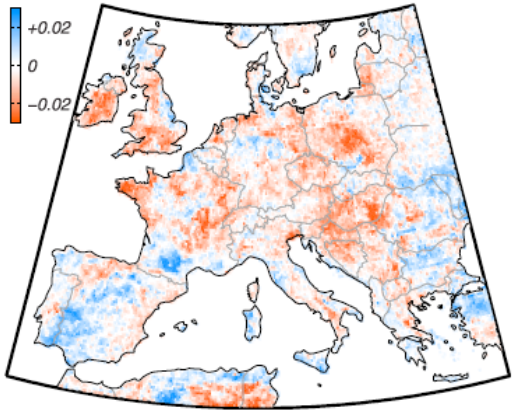
Albedo anomalies during the 2003 heatwave:

Constrasting feedbacks in the visible and near infrared!

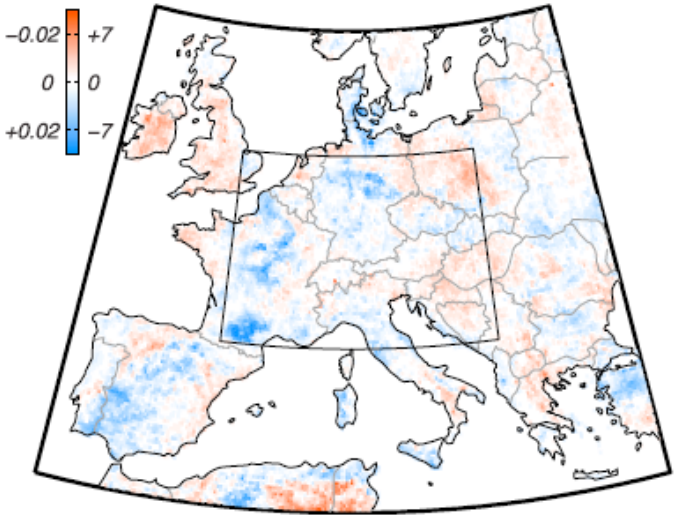
Anomalies in the visible



Anomalies in the near infrared (NIR)



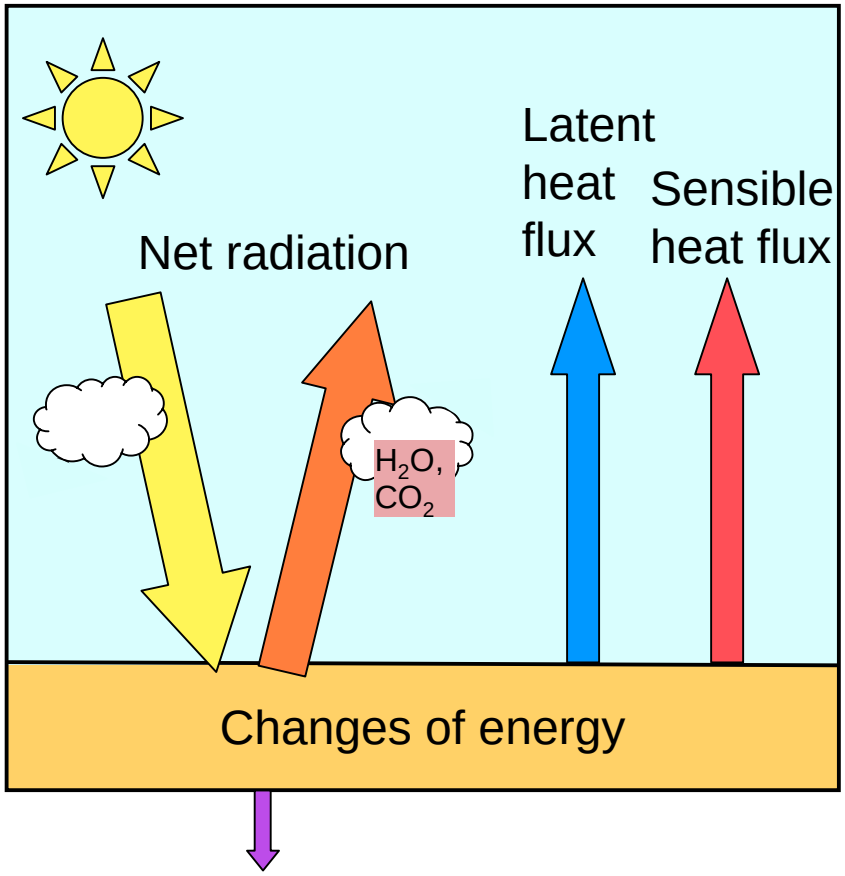
Net albedo anomalies



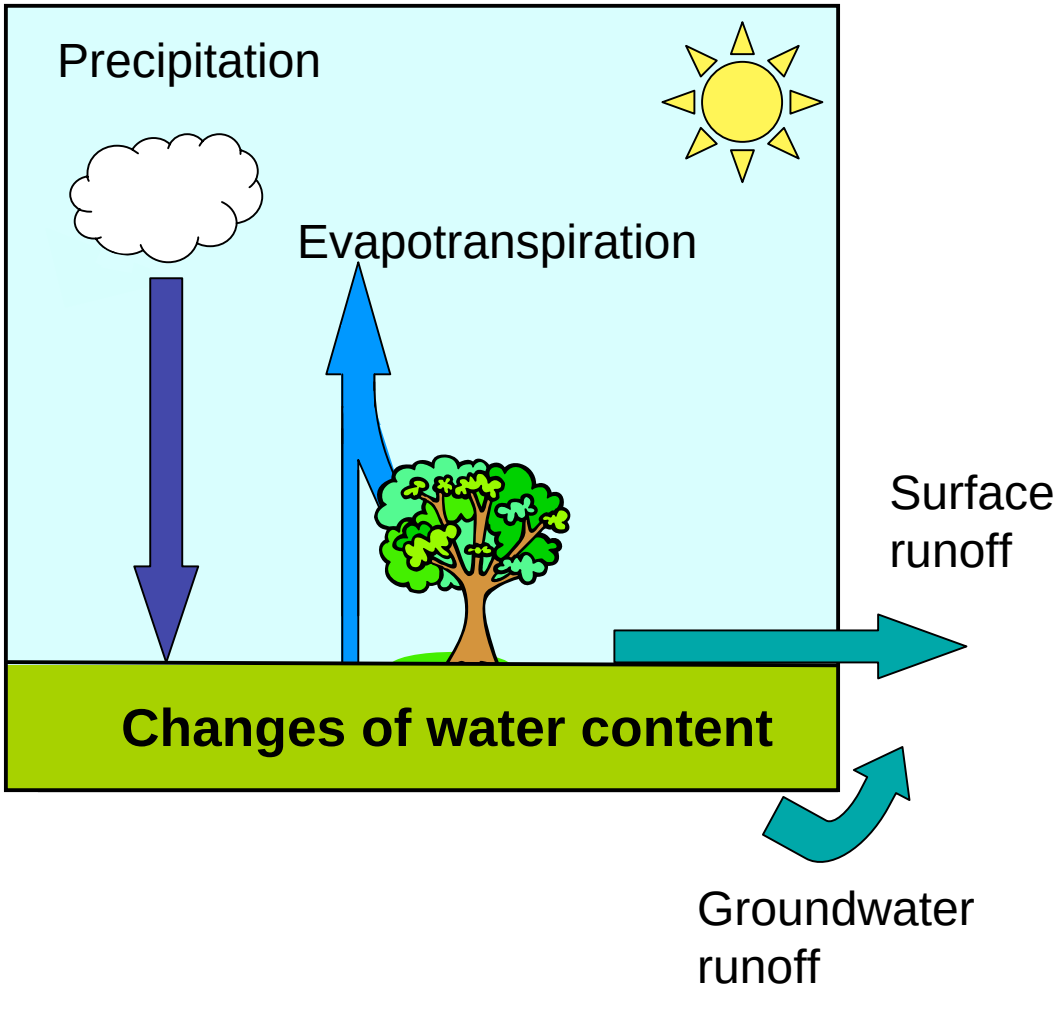
(Teuling and Seneviratne 2008, GRL)

Land energy and water balances

Land energy balance



Land water balance

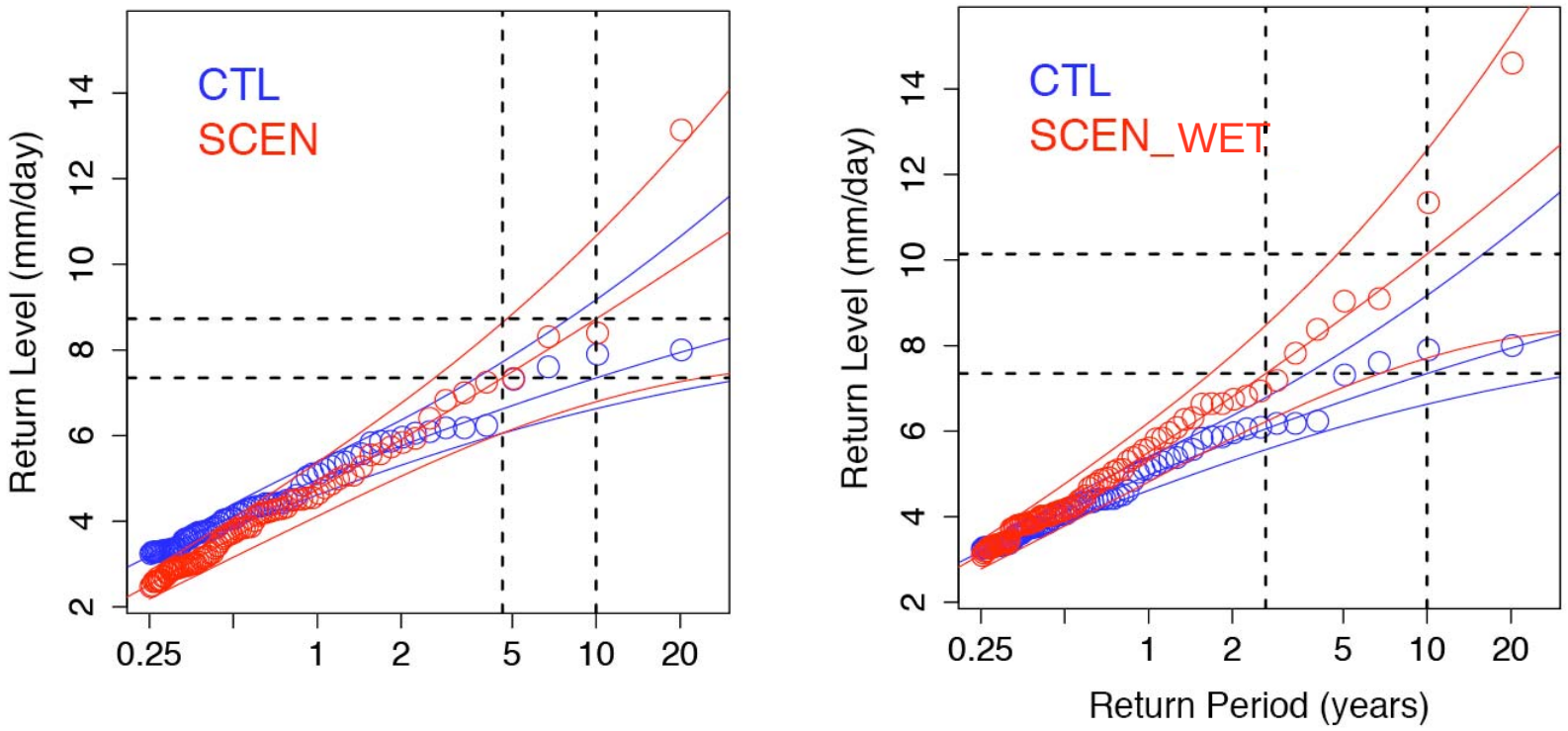


Outline

- Introduction
- Land-climate feedbacks and interactions:
  - Impact of soil moisture on temperature and precipitation
  - Impact on temperature variability, modifications with climate change
  - Other relevant feedbacks
- Discussion: Using observations to diagnose coupling and validate models
- Conclusions

Impact on precipitation (mean and extremes)

Return periods of 5-day summer (JJA) precipitation (Central Europe)



(Seneviratne et al. 2009, in prep.)